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Handbook *of* Die Design

Second Edition

- Custom-made automated systems
- Coating of tools for durability
- Specialized hardware components
- Strain hardening of materials

Ivana Suchy

The McGraw-Hill Companies

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CHAPTER 1
BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

1-1 SHEET-METAL STAMPING IN COMPARISON WITH OTHER METAL FABRICATING PROCESSES

In today's practical and cost-conscious world, sheet-metal parts have already replaced many expensive cast, forged, and machined products.

The reason is obviously the relative cheapness of stamped, or otherwise mass-produced parts, as well as greater control of their technical and aesthetic parameters. That the world slowly turned away from heavy, ornate, and complicated shapes, and replaced them with functional, simple, and logical forms only enhanced this tendency. Remember old bathtubs? They used to be cast and had ornamental legs. Today they are mostly made of coated sheet metal, if not plastics. Manufacturing methods for picture frames, chandeliers, door and wall hardware, kitchen sinks, pots and pans, window frames, and doors were gradually replaced by more practical and less costly techniques.

But, sheet-metal stampings can also be used to imitate handmade ornamental designs of previous centuries. Such three-dimensional decorations can be stamped in a fraction of time the *repoussé* artist of yesterday needed.

Metal extrusions, stampings, and forgings, frequently quite complex and elaborate, are used to replace handmade architectural elements. Metal tubing, metal spun products, formings, and drawn parts are often but cheaper substitutes of other, more expensive merchandise.

Metal stampings, probably the most versatile products of modern technology, are used to replace parts previously welded together from several components. A well-designed sheet-metal stamping can sometimes eliminate the need for riveting or other fastening processes (Fig. 1-1). Stampings can be used to improve existing designs that often are costly and labor-intensive. Even products already improved upon, with their production expenses cut to the bone, can often be further improved, further innovated, further decreased in cost.

The *metal stamping die* (Fig. 1-2) is an ideal tool that can produce large quantities of parts that are consistent in appearance, quality, and dimensional accuracy. It is a press tool capable of cutting the metal, bending it, drawing its shape into considerable depths, embossing, coining, finishing the edges, curling, and otherwise altering the shape and the outline of the metal part to suit the wildest imaginable design concepts. Figure 1-3 shows samples of these products.

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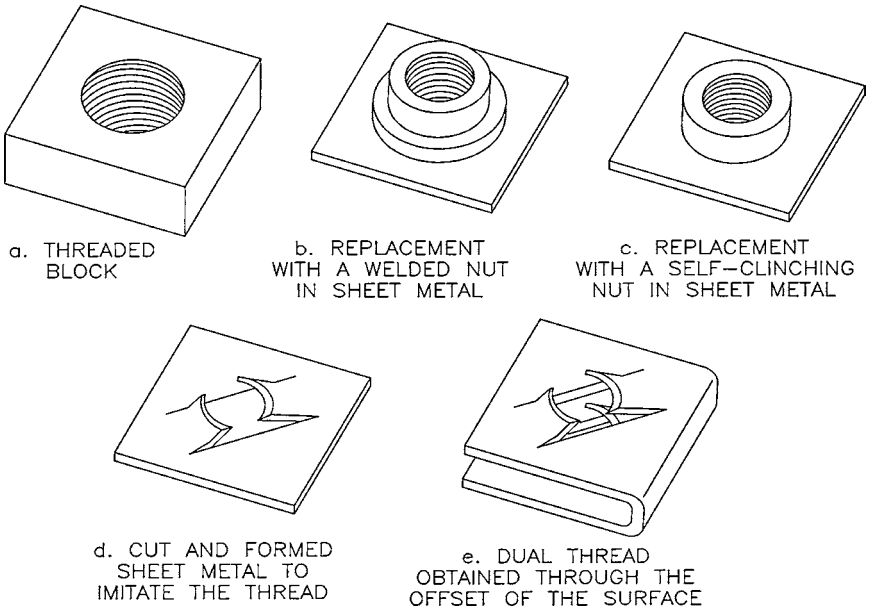
a. THREADED BLOCK
b. REPLACEMENT WITH A WELDED NUT IN SHEET METAL
c. REPLACEMENT WITH A SELF–CLINCHING NUT IN SHEET METAL
d. CUT AND FORMED SHEET METAL TO IMITATE THE THREAD
e. DUAL THREAD OBTAINED THROUGH THE OFFSET OF THE SURFACE

FIGURE 1-1 Threaded part, replaced by other, less expensive means.

The word "die" in itself means the complete press tool in its entirety, with all the punches, die buttons, ejectors, strippers, pads, and blocks, simply with all its components assembled together.

When commenting on these little technical ingenuities, it is important to stress the role of designers of such products, both artistic and technical. Their thorough knowledge of the manufacturing field will definitely enhance not only the appearance, but the functionality, overall manufacturability, and cost of these parts.

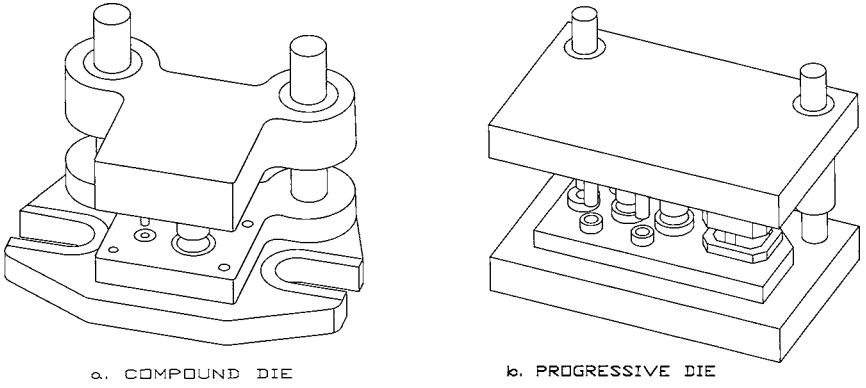

FIGURE 1-2 Metal stamping dies.

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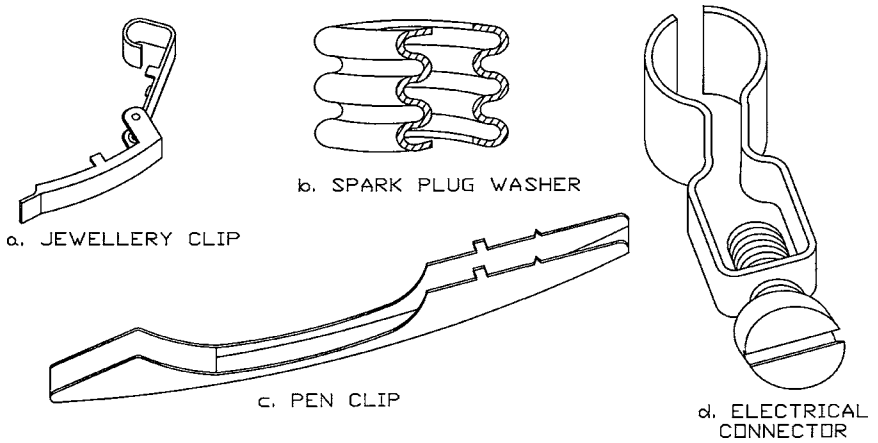

FIGURE 1-3 Various sheet-metal products.

Metal stamping die production output can be enormous, with huge quantities of high-quality merchandise, as shown in Figs. 1-3 and 1-4; pouring forth from the press. For that reason technical ignorance is not readily excusable, as the equal quantities of rejects can be generated just the same way.

1-1-1 Grain of Material

Often, parts produced by various manufacturing methods can be redesigned to suit the sheet-metal mass production (Fig. 1-5).

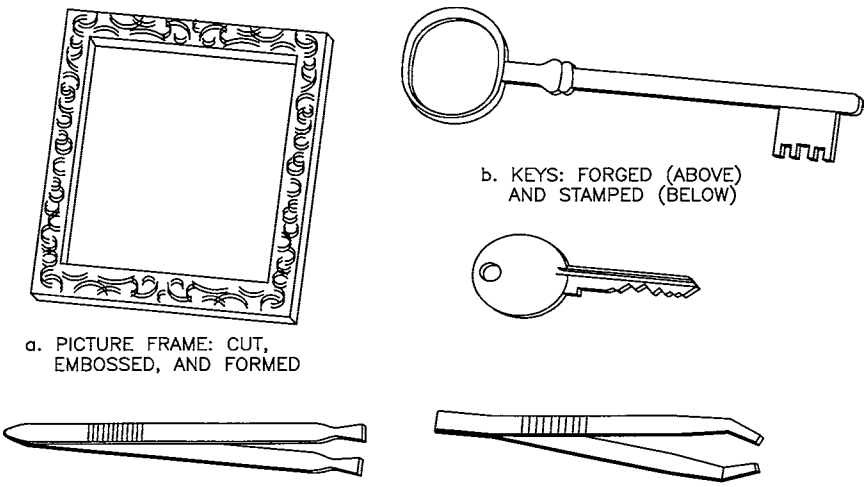
a. PICTURE FRAME: CUT, EMBOSSED, AND FORMED
b. KEYS: FORGED (ABOVE) AND STAMPED (BELOW)
c. TWEEZERS: CAST (ON LEFT) AND THEIR SHEET–METAL REPLACEMENT (ON RIGHT)

FIGURE 1-4 Metal-stamped replacements.

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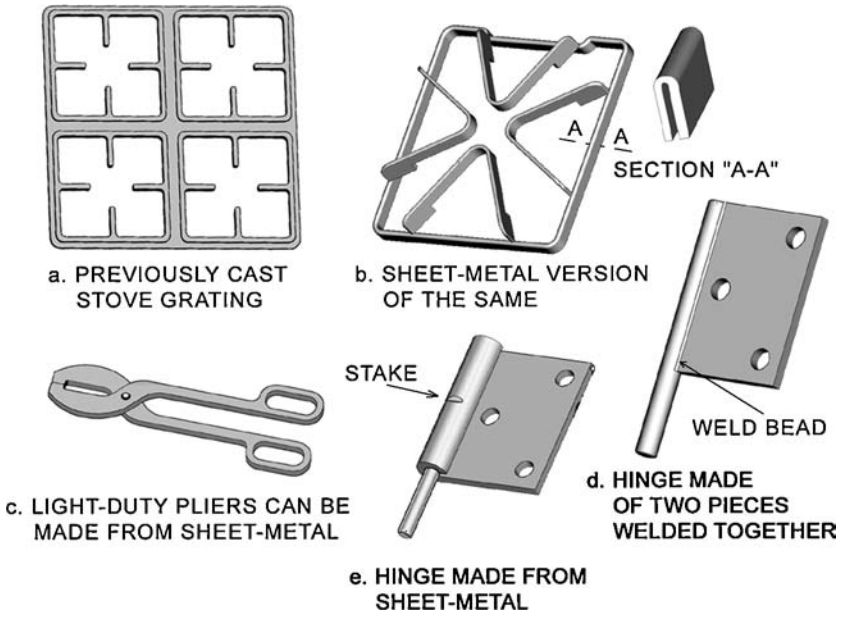

FIGURE 1-5 Additional sheet-metal replacements.

When designing such replacements, there are several aspects to be evaluated. The first and probably the most important is the grain of material (Fig. 1-6).

Sheet metal of every form, be it a strip or a sheet, displays a definite grain line. It is the direction along which the material was produced in the mill-rolling process. In coils, the grain direction always runs lengthwise, parallel with the longer edge. The grain direction

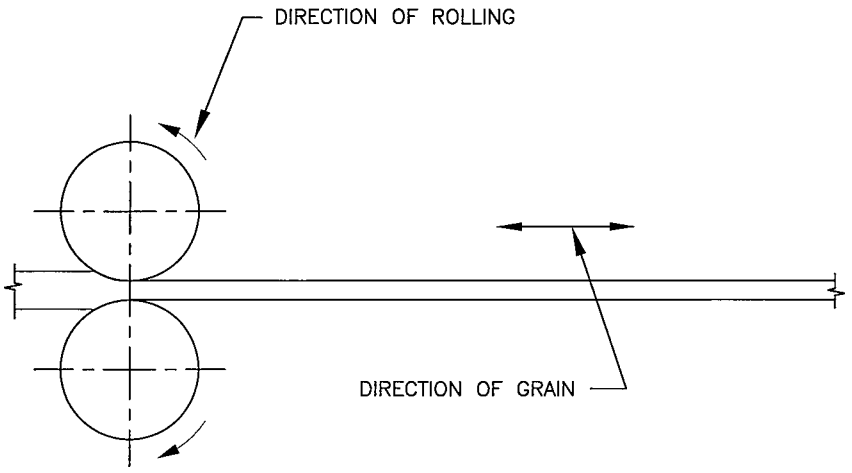

FIGURE 1-6 Grain of materal in sheet-metal strip.

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in sheets may vary, and designers must always make themselves familiar with it prior to planning a production run of any kind.

In contrast, cast or forged parts display a different grain direction, and in sintered powder metal parts the grain is completely gone. For this reason, each of these manufacturing methods can be used to produce items for different applications.

For example, a part, shown in Fig. 1-7, will display a different reaction to various forces and stresses when made by the forging method than when obtained through other manufacturing processes.

Where the forging would possess a great resistance to tensile and compressive forces along the *A-A* line, the same part, when made from sintered powder metal, may break or collapse under the same force.

With this shape being cast, the location of the gate is of extreme importance, as it influences the part's sturdiness in various directions. In the casting gated at the longer end (as pictured in Fig. 1-7*b*), the opposite end will be more susceptible to breakage, as the molten metal will reach that portion later, when already cooling down. The existence of an opening in that area will divide the flow of material and thus create a so-called knit line, along which a separation, resulting in defects and possible breakage, may occur.

The same casting, when gated in the middle (Fig. 1-7*c*), will have an equal breakage proneness at both ends. However, these ends will be somewhat sturdier, as the molten metal will reach them sooner than in the case of Fig. 1-7*b*. Of course, the existence of openings may have the same detrimental effect described earlier.

A similar product, made of sheet metal, as pictured in Fig. 1-8, will also display a grain-dependent behavior; the part with the lengthwise grain will be considerably sturdier along the *A-A* line of force than the same shape positioned across the grain line.

Where used sensibly, the grain in sheet-metal material can serve as a backbone of future products. In formed parts where bends are oriented perpendicularly to the grain of material, such bends are rarely seen cracking or becoming distorted, and the whole structural

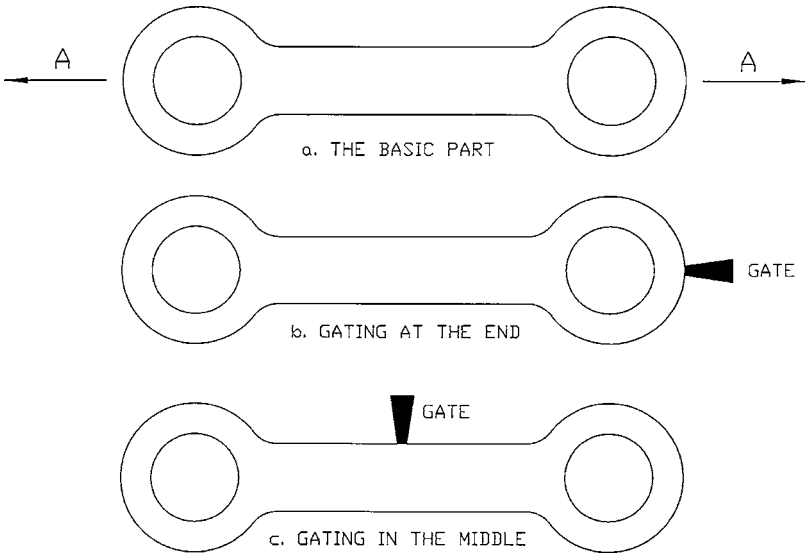

FIGURE 1-7 Forces applied to a casting.

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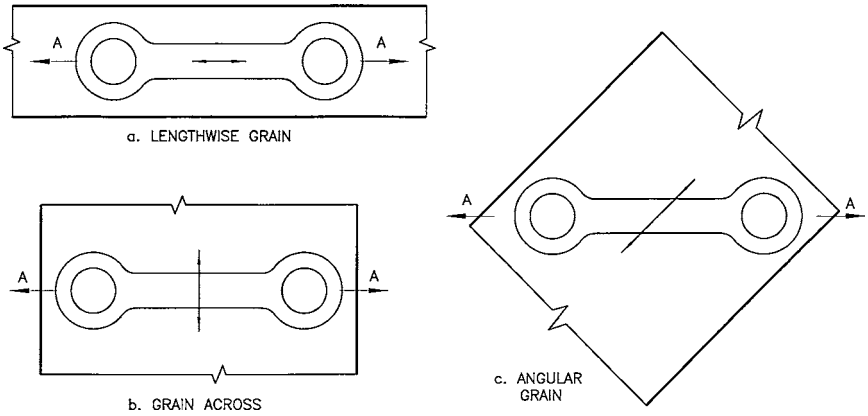

FIGURE 1-8 Grain variation in sheet-metal strip.

consistency of the part is greater. Where such bends "across the grain" cannot be achieved, bends under an angle should be attempted (see Fig. 1-9). In parts with bends in both directions (Fig. 1-9*b*), a 45° deviation from the grain line can be extremely helpful.

Aside from other advantages, sheet-metal parts are stronger and sturdier than parts produced by many other manufacturing methods. For example, die cast parts can be impressive with their intricate shapes, nonconcentric rounds, and full-bodied mass. But they have no distinct grain direction, and where strength is required their increased thickness often serves as a substitute for sturdiness (see Fig. 1-10).

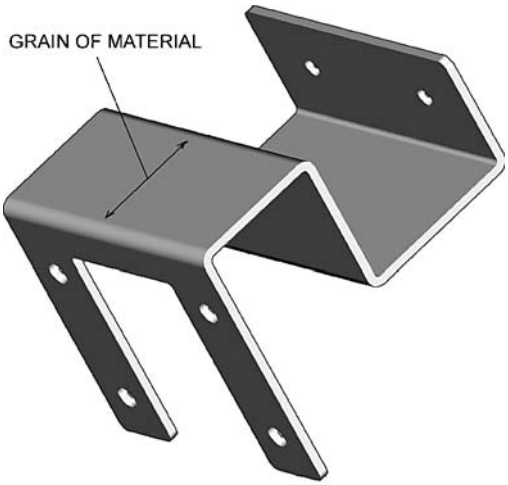

FIGURE 1-9 Grain of material in bending.

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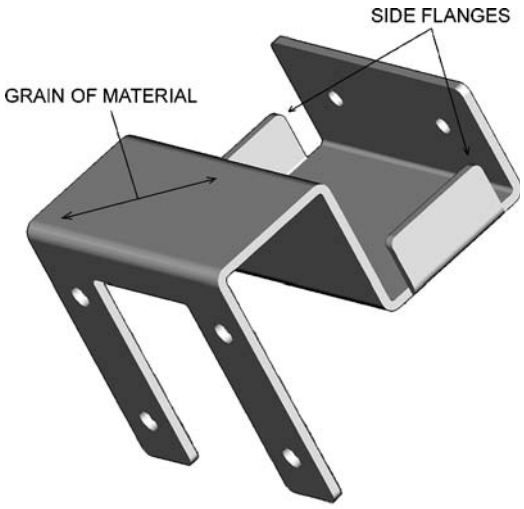

b. BENDS AT 45° ANGLE

FIGURE 1-9 (*Continued*)

Sintered metals have no grain-generated backbone at all and may fail if used in high-stress applications. Forged materials do have their strength and sturdiness, but this is, again, outweighed by their bulkiness, as shown in Fig. 1-11*a*. Same with extruded materials (Fig. 1-11*b*): the grain is there, the strength is there, the columnar strength is impressive, but the increased bulkiness cannot be overlooked. Additionally, the span of applications for these products is limited and highly specific.

Plastic parts, similarly to cast products, have but the material flow to depend on and that provides them with more defects than support. And since plastic materials are generally of

FIGURE 1-10 Sample of a cast part.

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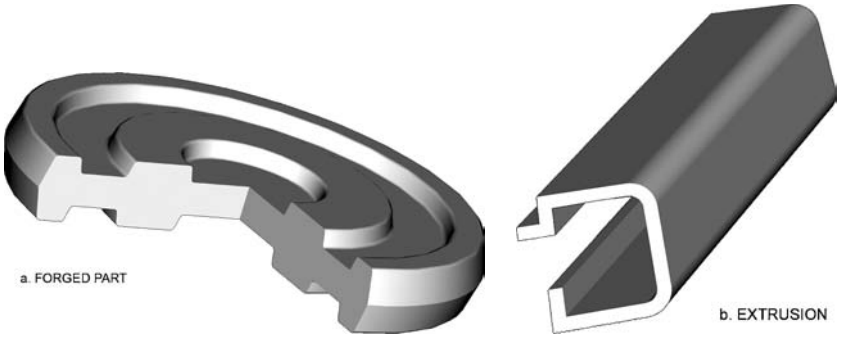

FIGURE 1-11 Forged and extruded parts.

quite low strength when compared to metal parts of the same shape, they suffer from cracking when stressed or flexed, often brittle, pestered with serious aging problems, and greatly affected by weathering effect. They are almost useless in many applications where sheet metal can substitute for them with ease. Yet, for some reason, today's manufacturers often go into extremes of supporting a fragile plastic insert with a sturdy wire mesh or producing a complicated sheet-metal structure covered by a plastic wrapper, just to be able to use plastics.

Where fillers are used in plastics moldings, the proneness of such parts to cracking can be greatly enhanced, with dependence on the percentage of filler material utilized. And considering the pressure today's plastic parts' production places on the petroleum industry, we actually may have no plastic parts to speak of 50 years down the road, especially when taking into account the enormity of our mass production and mass consumption.

1-1-2 Edge Formation

Another important aspect to be considered when designing sheet-metal replacements for parts manufactured by other methods is the formation of the edge. A cast part (Fig. 1-12*a*) will always exhibit a parting line to some degree. The visibility of this line is dependent on tool quality; with well-manufactured and well-maintained tooling, the line can be almost invisible, but with worn-out dies, rough machining, and crude assembly and fit, that area may bulge out and perhaps even show a burr at some places. The existence of draft angle in cast parts is another necessity the designer has to take into account.

If the same part were forged, it will have the edge characteristics similar to those of its cast counterpart. Sheet-metal products' edges will be completely different. With dependence on the thickness of material and clearance between the punch and die, the sheet-metal parts' cut or pierced edges will show a reasonably straight portion, with a slight distortion toward the surface opposite from the punch, as shown in Fig. 1-13. The mechanism prompting such distortion to emerge at all, along with the factors contributing to its width and volumnar growth, are explained in greater detail in Chap. 2.

Considering the terminology, here the word "die" describes the insert, which during the operation of the press receives the punch and retains the pierced slug or blanked part. Sometimes the term "die button" may be used interchangeably.

The burr on metal-stamped products is a great aid in evaluating the sequence of the manufacturing process, as it clearly indicates the direction of punching (or blanking) of each opening and of each cut.

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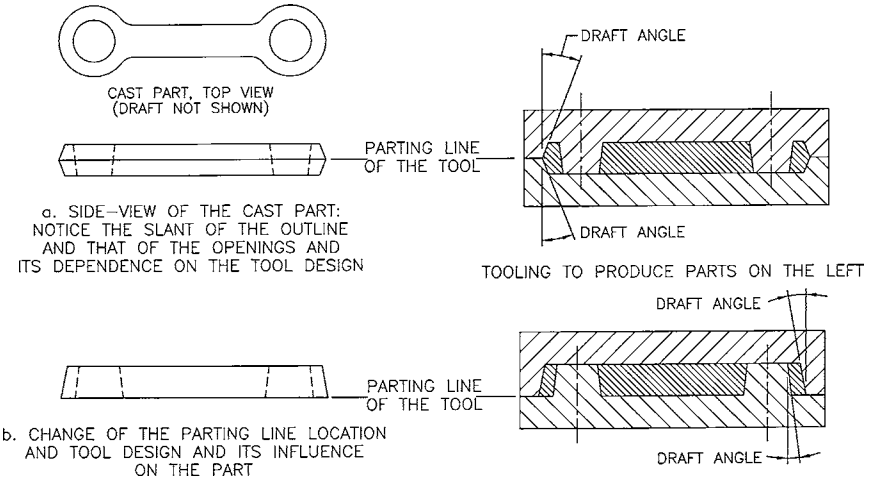
CAST PART, TOP VIEW
(DRAFT NOT SHOWN)
PARTING LINE
OF THE TOOL
a. SIDE–VIEW OF THE CAST PART:
NOTICE THE SLANT OF THE OUTLINE
AND THAT OF THE OPENINGS AND
ITS DEPENDENCE ON THE TOOL DESIGN
DRAFT ANGLE
DRAFT ANGLE
TOOLING TO PRODUCE PARTS ON THE LEFT
DRAFT ANGLE
PARTING LINE
OF THE TOOL
b. CHANGE OF THE PARTING LINE LOCATION
AND TOOL DESIGN AND ITS INFLUENCE
ON THE PART
DRAFT ANGLE

FIGURE 1-12 Side view of the cast product.

Drawn parts' edges are similar in that they display the characteristics of the cut metal, where produced from previously blanked material (see Fig. 1-14*a*). This is due to the action of blankholder, which retains the outer rim of the blank, while the middle of it is being drawn into depth.

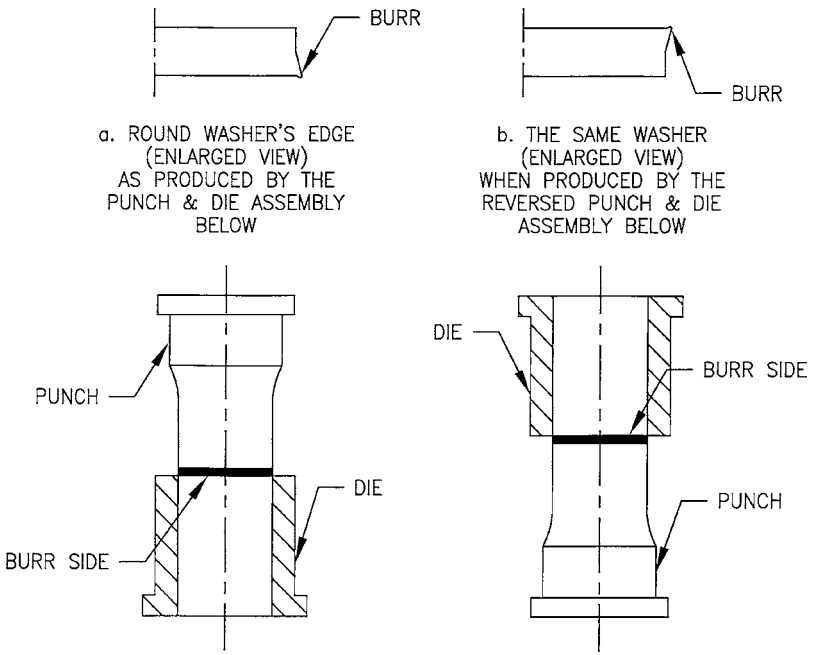

FIGURE 1-13 Edge formation in stamped parts.

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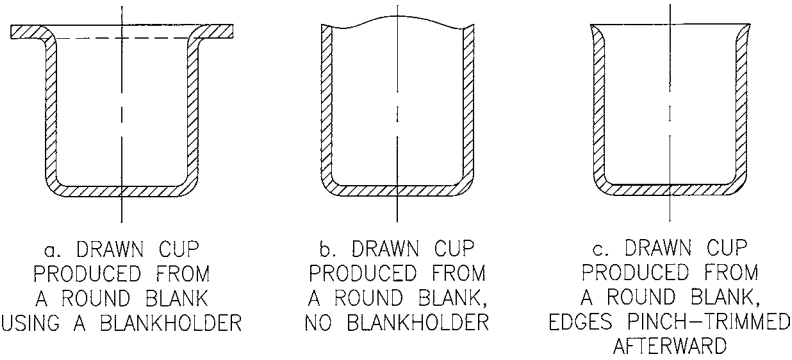
a. DRAWN CUP PRODUCED FROM A ROUND BLANK USING A BLANKHOLDER
b. DRAWN CUP PRODUCED FROM A ROUND BLANK, NO BLANKHOLDER
c. DRAWN CUP PRODUCED FROM A ROUND BLANK, EDGES PINCH–TRIMMED AFTERWARD

FIGURE 1-14 Edge formation in drawn parts.

Where no blankholder is employed, the drawn part is usually expelled through the die right after drawing, in a single, continuous motion of the press. The edges of such a part are wavy and uneven, as shown in Fig. 1-14*b*.

A drawn cup produced from a blankholder-restrained blank and trimmed afterwards, retains a portion of the outer radius of the previously formed flange, which gives the edge of a shell a knife-resembling sharpness (see Fig. 1-14*c*).

The formation of the cross section of the drawn portion further influences the product's characteristics. There is often some thinning of the wall due to the drawing process, and the deeper the draw, the thinner the wall may become (Fig. 1-15).

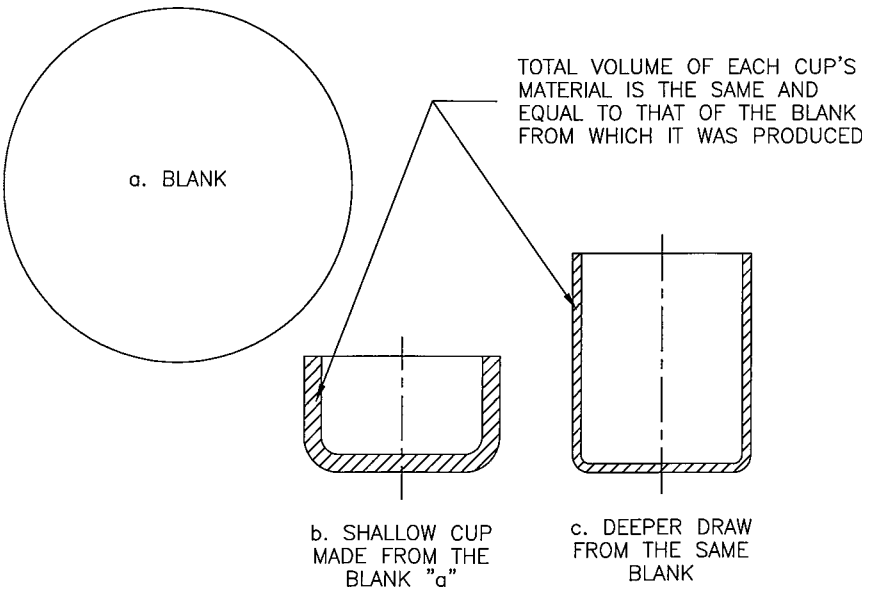
a. BLANK
TOTAL VOLUME OF EACH CUP'S MATERIAL IS THE SAME AND EQUAL TO THAT OF THE BLANK FROM WHICH IT WAS PRODUCED
b. SHALLOW CUP MADE FROM THE BLANK "a"
c. DEEPER DRAW FROM THE SAME BLANK

FIGURE 1-15 Volumnar changes in drawing operation.

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The reason for this is obvious: The material needed for the expanded length of the drawn portion has to be taken from somewhere, and practically (and mathematically) the volumnar content of that section must be equal to that portion of the flat piece from which it was produced.

1-2 WHAT CONSTITUTES SUITABILITY FOR DIE PRODUCTION?

When evaluating a part for die production, the most restrictive aspect to be considered is the cost of the tooling. To build a metal stamping die is a costly process, involving many people, many machines, and several technologies. For that reason, the demand for tooling must first be economically justified.

The quantitative demands per given time span should be evaluated first, because a scenario of 50,000 washers to be delivered each month requires a different treatment from 50,000 washers to be delivered each week.

A correct evaluation of the problem must be performed on the basis of:

- Availability of the appropriate press
- The equipment's running speed
- The length of production shifts
- Scheduling for the needed time interval

For a small run with few repetitions, a single line of tooling may be chosen. However, if the quantities are large and the time constraint exists, a multiple-part-producing tool must be built. Such a die, generating at least two or more complete parts with each stroke of a press, will speed up production admirably. But increasing the size of the tool necessitates the use of a larger and more powerful press and may even require a nonstandard width of a strip, which will certainly cost more and will have longer lead (i.e., delivery) times.

With parts other than simple washers, the shut height of the press versus the height of the part (and subsequently the height of the die) is another production-influencing factor. The width of the opening in the press plus the width of the proposed die must definitely be in congruence.

The possibility of reorders should be considered at this point, as they may result in an extended production run, greater material demands, and longer occupancy of the press. Such longer runs are usually beneficial from the economical standpoint, as they save on die-mounting procedures and press adjustments, while also decreasing the demand for quality control personnel involvement.

On the other hand, a problem of storage of these extra parts may arise along with the existence of temporarily unrewarded financial investments into the purchase of material, workforce compensation, taxes, utilities, and overhead. These all need to be taken into account since they will only increase the final cost of the product, long before it can be sold to a customer.

To properly evaluate the situation, all applicable expenditures should be added up as follows:

1. Cost of the storage space (prorated rent or property taxes, cost of the building and improvements)
2. Cost of all packaging and repackaging material, storage containers, protective barriers, and insulation
3. Cost of stacking and restacking of parts, sorting them out, and discarding rusty or damaged pieces
4. Spoilage of possible storage-sensitive material and the scrap rate

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5. Cost of raw material and other production-related necessities
6. Overhead, such as electricity, cost of heating or cooling, water, and fuel applicable to the storage of parts
7. Cost of labor, including possible overtime
8. Cost of paperwork involved with storage and subsequent handling of products
9. Interest rate at which the monies allocated to the above activities could have generated when invested otherwise

The combined expenses 1 through 9, when added up, should be equal to or less than the combined:

1. Cost of the removal of a die from the press
2. Cost of the installation of a die in the press (for the subsequent run)
3. Cost of the machine's downtime during the die removal and installation
4. Cost of the press operator's standby, if applicable
5. Cost of the press adjustments and trial runs
6. Cost of the first piece inspection and the cost of further adjustments and approvals, if applicable
7. Cost of the extra material and supplies, which must be purchased ahead of the time even if not immediately utilized
8. Overhead, such as cost of electricity, heating, cooling, water, and fuel
9. Cost of all subsequent billing and paperwork
10. Combined interest (per going rate) the finances allocated to the above causes would have generated when invested otherwise

The length of each run and its influence on the need for sharpening and maintenance of tooling must be evaluated for the entire production run. Should a maintenance-related interruption be necessary, a possible split of the previously planned combined run should be considered.

A definite advantage of the die production is its unrivaled consistency in the products' quality and dimensional stability. In absence of design and construction mistakes, the die, once built, needs minimal amount of alterations, aside from regular sharpening.

Some dies, true, are more sensitive than others, which is mostly attributable to excessive demands on close tolerance ranges of parts and on the variation in material thickness. With some bending and drawing operations, the consistency in hardness of stock can be essential as well. But a regular die, well designed and well built, can deliver a great load of products before its punches begin to wear and a need for repair or sharpening arises.

Generally, it may be claimed that if the conditions of the die-operating process are kept the same and if the tool was not dropped off the forklift or similarly mangled, the parts from the die will emerge consistent with previous runs.

1-3 DESIGN CRITERIA FOR DIE-MANUFACTURABLE PRODUCTS

Today's world places greater and greater demands on products and materials, from which they are made. Years ago, many designers never figured out stress and strain, elasticity, fatigue, or similar values. If it broke, then you just made it 2 inches thicker, or 3 inches, or 5 inches, whatever you preferred.

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But that is not how current manufacturing is governed. Resources are getting scarcer, perhaps even limited in some cases, and designers are forced to economize. After all, why should a car body be thick and heavy, when a thinner-gauge galvanized or galvannealed steel will bring about the same, if not better, results.

Demands for special alloys are continuously expanding, and they are in equal competition with all the new and increasingly better alloys that are being produced. Ferrous and nonferrous alloys, titanium and its and alloys, and alloys with traces of rare metals added for additional qualities are all available to fill that specific gap where they are needed.

Manufacturing methods are next on the list of economizing designers. Avoiding secondary operations whenever possible, designers apply cost-conscious strategies and planning not only in small shops, but in medium and large plants as well.

This certainly is a good approach to any given problem, since every product has its price. If manufacturing costs become greater than the value of a product, such an item becomes unsalable.

For these reasons, manufacturability of products is extremely important. Almost anything can be manufactured somehow, if people put their minds to it. But at what cost? And who will be willing to pay for it?

Out of this ever-present regard for price versus actual value, new methods are being devised daily, new approaches to old problems sought for. Crowds of engineers, designers, tool makers, model makers, and representatives of other professions are nit-picking new, almost new, or old problems, in an attempt to come up with a simple, straightforward, and cost-effective answer.

Sometimes, however, shortcuts are taken, where cheaper materials, thinner coatings, less durable tools, or less experienced labor are used. These steps are just what they present themselves as: shortcuts. They usually produce more returns, more repairs, more problems around their drawbacks, and even more expenses. There is a time and a place for everything, but these remedies are not always helpful. You pay for them later.

A good, sound design and overall manufacturability cannot be replaced by trinkets. The old saying “if it isn’t good, fix it” should perhaps be replaced by “if it isn’t good, redesign it!”

1-3-1 Manufacturability Aspects

The manufacturability of products depends on many factors. Sometimes a lack of space may prevent a mechanic from reaching the area of concern, and long hours may be lost before this obstacle is overcome. Or a wrong sequence of operations will cause the final product to become distorted. Sometimes an adhesive may not hold because the part was not degreased enough, or a screw may fall out because someone forgot to add that second nut or a drop of Loctite.

In die work, the manufacturability of parts is dependent on much narrower range of influences. The main areas of concern are

1. Grain direction of the material
2. Openings, their shape and location
3. Bends and other three-dimensional alterations to the flat part, their shape and location
4. Outline of the part and its size
5. Applicable tolerance ranges
6. Surface finish, flatness, straightness, and burr allowance

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1-3-1-1 Grain Direction of the Material. The ever-present grain of material must be taken into consideration first. Unless absolutely necessary, it should not appear alongside a bend, a joggle, or any other deflection and elevation in the part's surface.

Every sheet-metal material behaves differently alongside the grain line and across it. Forming, drawing, and even simple punching may sometimes show differences in the size and shape of the hole when evaluated for the grain influence. An extruded opening, shown in Fig. 1-16, illustrates this claim. By cutting across the grain line, the material behaves almost as if constantly in tension, which, when forcibly removed by the cutting process, causes the material to back off.

If a bracket such as the one shown in Fig. 1-17*a* will be rotated 90° and positioned on the strip with its bends along the grain line, these flanges may sometimes crack in forming or even much later, in service, afterward. For that reason, wherever the problem of multiple bends occurs and there is no chance of avoiding their placement alongside the grain line, an angular positioning on the strip or sheet, shown in Fig. 1-17*b*, should be considered.

Such a grain-line pattern should be used quite habitually with materials of the 6061-T4 (T6) aluminum group, as they are prone to cracking. Especially if, for some reason, parts are belt-sanded in flat prior to bending, their proneness to cracking will be enhanced. A greater bend radius, as well as vibratory sanding, or belt-sanding under an angle, may help to alleviate the problem to a degree.

In parts with several formed sections, the shear strength and resistance to columnar stress of their flanges will vary with their variation from the material's grain, as shown in Fig. 1-18. Should a force *A,* parallel with the grain line, be applied to the bend-up section, the greatest shear strength will be encountered. However, we already know that bends running parallel with the bend line are prone to cracking in forming and are not recommended.

Intermediate shear strength will be encountered in the direction of the *C* force line in Fig. 1-18*a*, whereas the *B* force line will display the least shear strength, as the flange may tend to bend under it. Whenever a bent-up flange is acted upon by a secondary bending force, it has a tendency to follow that force's direction only if consistent with the initial movement of the flange in forming. A force applied against the direction of bending will not flatten the material, but will break it.

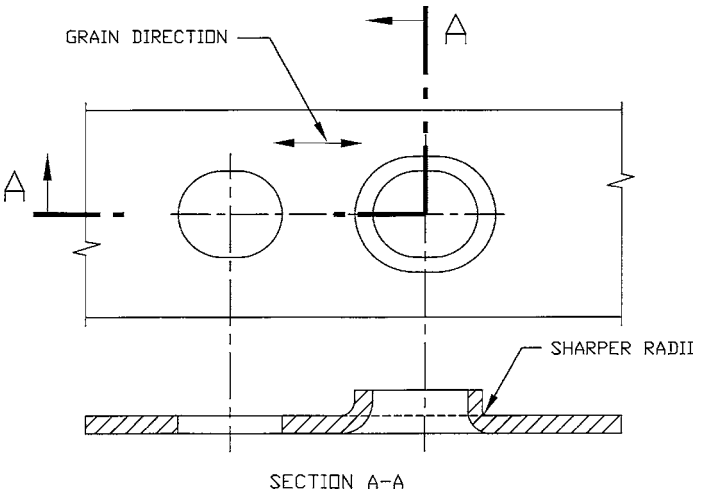

FIGURE 1-16 Elongation of openings (exaggerated) caused by the direction of grain.

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BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

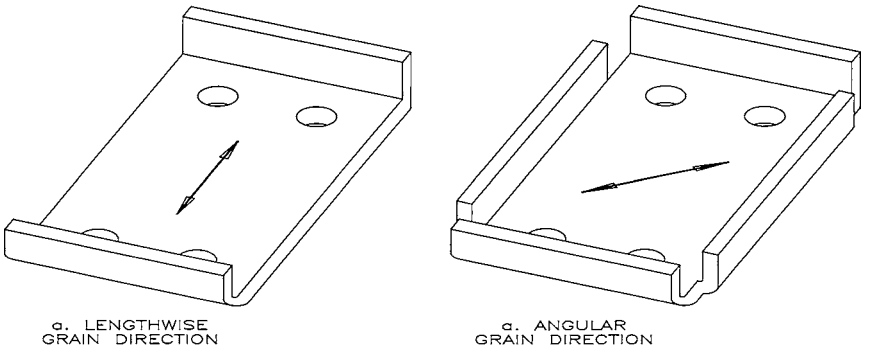

FIGURE 1-17 Grain direction in formed sheet-metal parts.

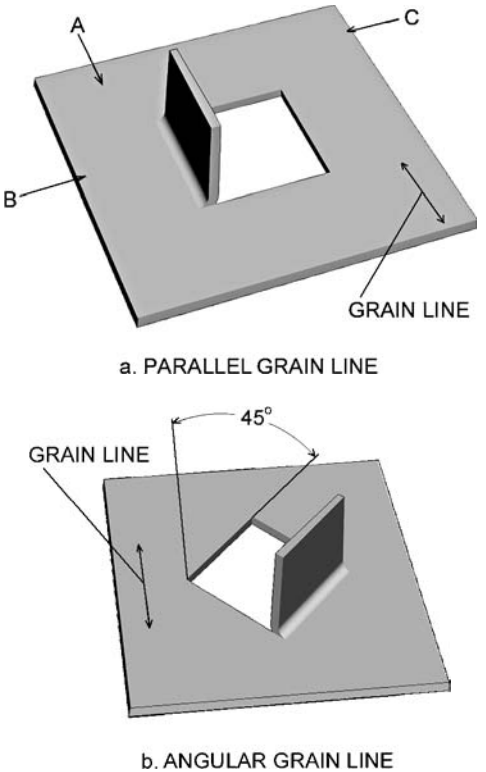

FIGURE 1-18 Stresses and their relationship to the direction of grain. (*From Frank W. Wilson*, "Die Design Handbook," *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

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Bending style shown in Fig. 1-18*b*, with flanges at 45° off the grain line, is considered a fair practice.

The value of the bend radius is another factor influencing the part's behavior in forming—the smaller the radius, the greater the material's proneness to cracking. There is a certain minimal bend radius for various materials and thicknesses, which is discussed in Chap. 8.

1-3-1-2 Openings, Their Shape and Location. Openings in the part should not be located too close to each other and certainly not too close to the edge of the sheet or strip (Fig. 1-19). At this point, it should suffice to compare the sheet-metal cutting operation to that of slicing a block of Swiss cheese. The closer to each other the cuts are placed, the more distorted they will be.

The shape of openings other than rounded, has a considerable effect on the part's behavior in further manufacturing as well as in service (Fig. 1-20). Sharp edges in cutouts become the points of accumulated stresses and may turn into points of failure. Sharp edges are also difficult to protect from rust and corrosion, which may seep into the part through these areas. For that reason, rounded edges are preferable whenever possible.

Some minimal dimensions for punched parts are shown in Fig. 1-21. Should an opening be located too close to a bend, the recommended practice would be to first produce the bend and only subsequently to pierce the opening. By following this procedure, a greater dimensional stability can be achieved. Because if such an opening is pierced first and the bend produced afterward, distortion of the opening will occur (Fig. 1-22).

1-3-1-3 Bends and Other Three-Dimensional Alterations to the Flat Part, Their Shape and Location. The location of formed portions and their dependence on the direction of grain was already addressed in Sec. 1-3-1-1. In some situations, however, bending along all four edges of a square or rectangular opening cannot be avoided. This is a condition in which the results of bending along the grain and bending perpendicularly to it differ. There are charts and guidelines ready to provide us with the data on the size of the bending radius and bending allowance in either situation. But often, a simple trial run and a careful examination of the bend may serve the purpose.

A slightly different problem is the formation of flanges (i.e., sides) in a four-sided enclosure. Here a question of the most suitable joining technique of side flanges is often brought up. Often, the sides of such a unit can be left with a small gap for welding (Fig. 1-23*a*), or be provided with an additional bent-up flange and spotwelded together (Fig. 1-23*b*).

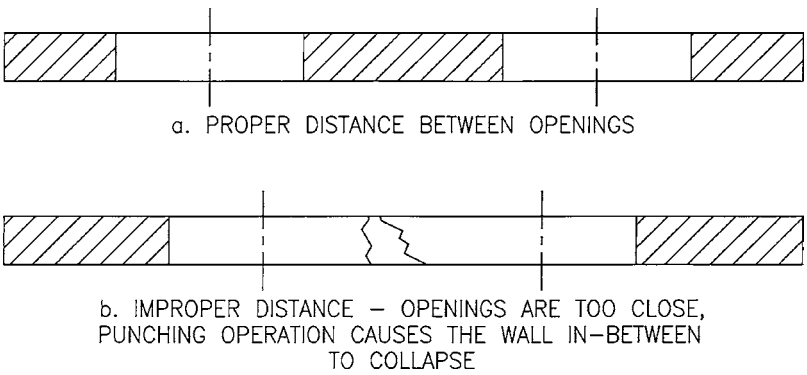
a. PROPER DISTANCE BETWEEN OPENINGS
b. IMPROPER DISTANCE – OPENINGS ARE TOO CLOSE, PUNCHING OPERATION CAUSES THE WALL IN–BETWEEN TO COLLAPSE

FIGURE 1-19 Distances between pierced openings.

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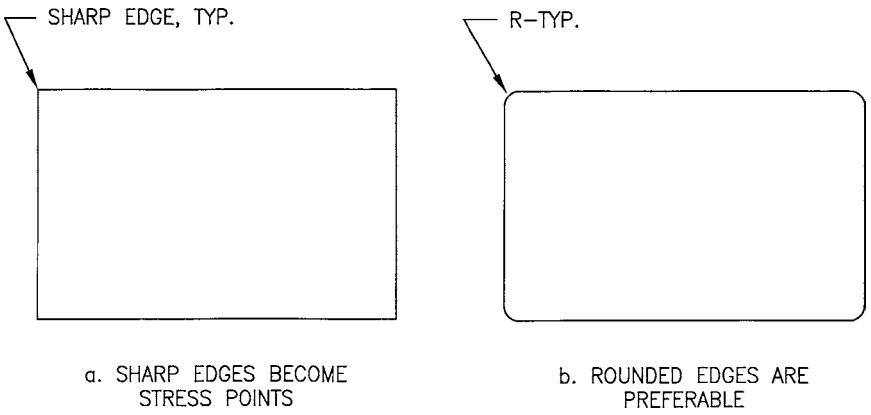

FIGURE 1-20 Openings other than round.

Where the enclosure has not only four sides but the frontal, or face flanges as well (Fig. 1-23*c, d, e*), this dilemma is still greater. Basically, there are but three solutions to this problem. For face plates, the gaps between the joining flanges can be weld-filled and sanded smooth. For unexposed areas, or where another plate is to be used as a cover, rough-sanding to flatten the surface may be good enough.

Gaps between the flanges may be large, small, or almost nonexistent. Their size and quality depends on the bend calculation, condition of tooling, and experience of the operator (in manual bending situations).

All bent-up portions should be provided with proper bend relieves (Figs. 1-24 and 1-25). These not only ease the bending process but also prevent the material from being pulled in the wrong direction, wrinkled, or torn.

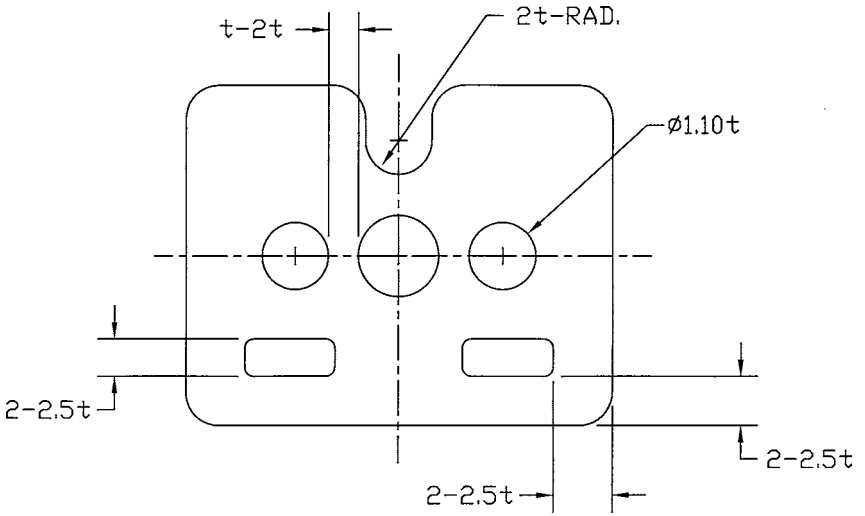

FIGURE 1-21 Minimal practical punching and blanking dimensions (t = material thickness).

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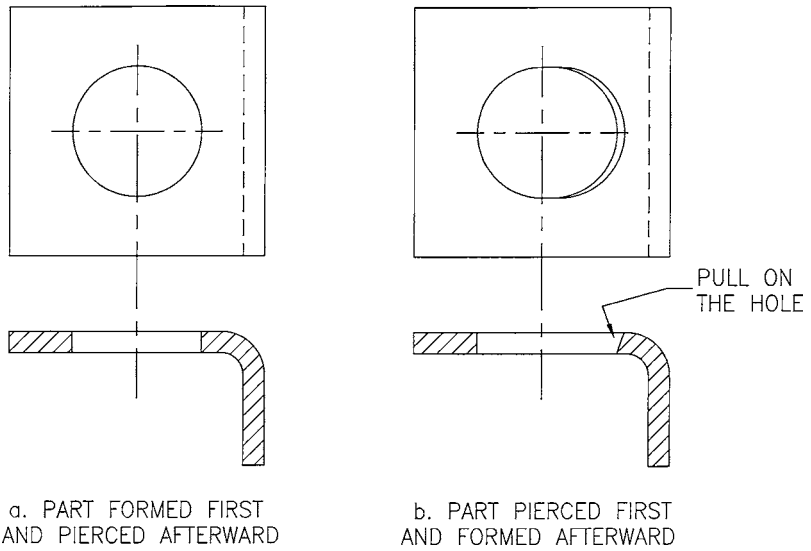
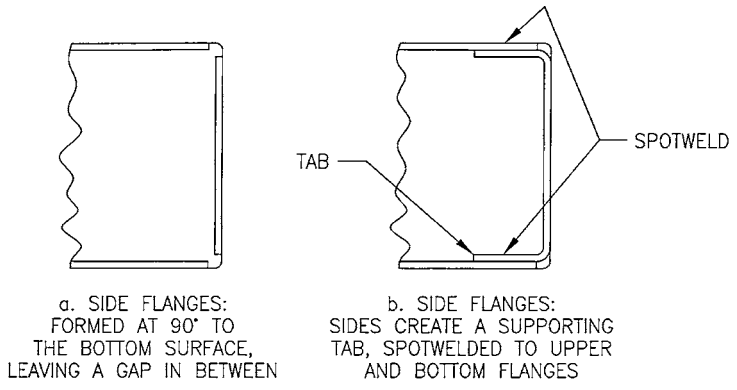


FIGURE 1-22 Influence of bending and piercing sequence of operations.



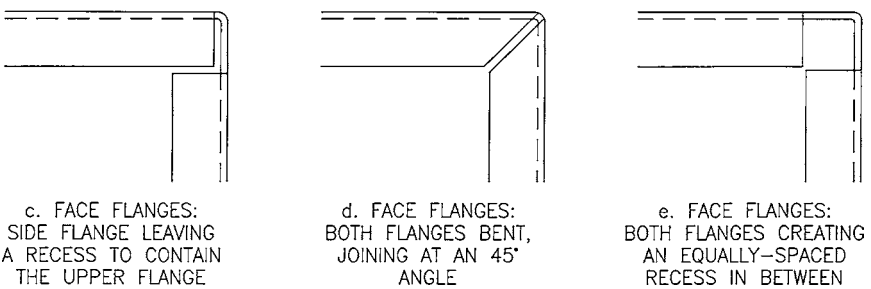


FIGURE 1-23 Different methods of joining side and face flanges.

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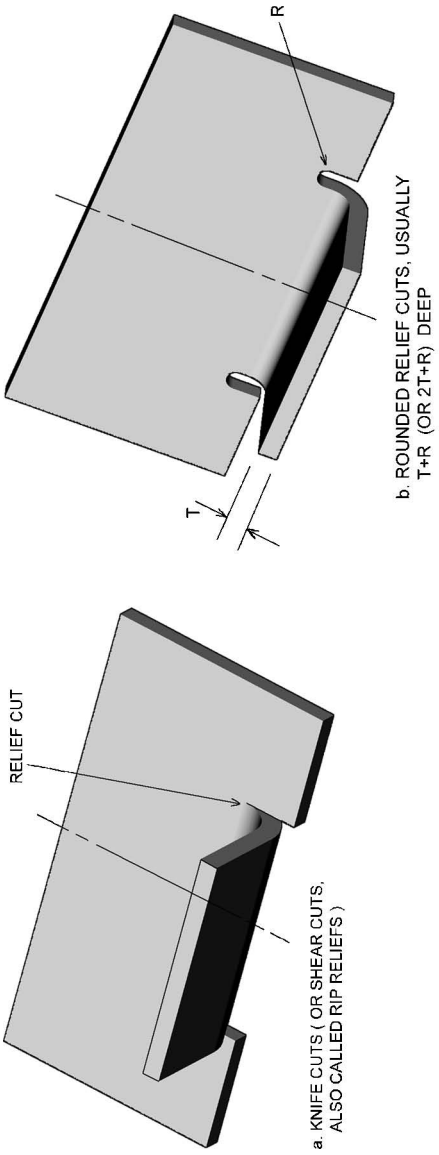
RELIEF CUT
a. KNIFE CUTS (OR SHEAR CUTS, ALSO CALLED RIP RELIEFS)
R
T
b. ROUNDED RELIEF CUTS, USUALLY T+R (OR 2T+R) DEEP
SAME RELIEF AS SHOWN ON THE OTHER SIDE
BEND LINE
c. DEEP ROUNDED RELIEFS, CENTERED AROUND THE BEND LINE

FIGURE 1-24 Samples of bend reliefs.

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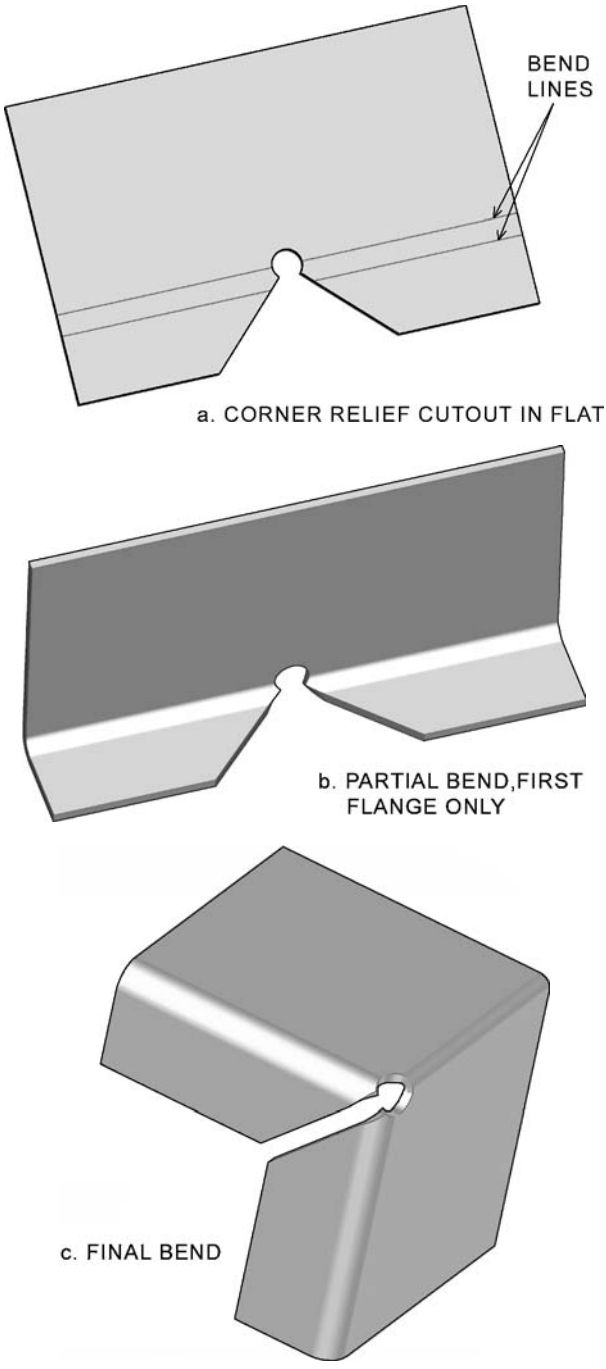

FIGURE 1-25 Sample of corner relief.

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On occasions where all sides of a box are to be butted against each other, a circular bend relief can sometimes be utilized. A sample of such bend relief is shown in Fig. 1-25. Here the round cutout removes that portion of material that would have been severely damaged by the bending operation.

In Fig. 1-26, some additional types of bend reliefs are shown. The most common style (Fig. 1-26*b*) is widely prevalent throughout the sheet-metal industry. However, even bending techniques such as those marked "incorrect" in Fig. 1-26*c* and 1-26*d* may sometimes be utilized in combination with an aggressively spring-backed pressure pad. Sometimes there would be no tear marks, cracks, or distortion visible on such parts, unless the circumstances were extreme. But years later, already in service, the usually sturdy sheet-metal products may fail and break down because of the insidious and destructive effect of nonrelieved stresses, created by a harsh bending process.

1-3-1-4 Outline of the Part and Its Size. Razor-sharp edges (or feather edges) must be avoided, especially if the parts are to be further handled by hand. These types of cuts are detrimental to the tooling as well, for if a punch does not engage the majority of its surface area in cutting, it tends to lean toward one side, breaking afterward. Figure 1-27 shows examples of edge trimming.

In metal stamping, feather edges may result in formation of chips and small break-offs, which tend to remain on the die surface and impair further work. These little pieces of metal may scratch the advancing strip, may become embedded in finished parts, forced into their surface by the die operation, or may even be randomly flung around, endangering the shop personnel.

Often, it may be quite tempting to use a round punch for a half-round cutout, as shown in Fig. 1-27*c*, or fudge the edges as in Fig. 1-27*e*, especially if there is a small strip of material between the part and the edge of the strip. Sometimes we just want to believe that this little sliver of metal will form an adequate support and prevent the punch from swaying aside. However, the width of the strip may come from the mill on a minus tolerance side and

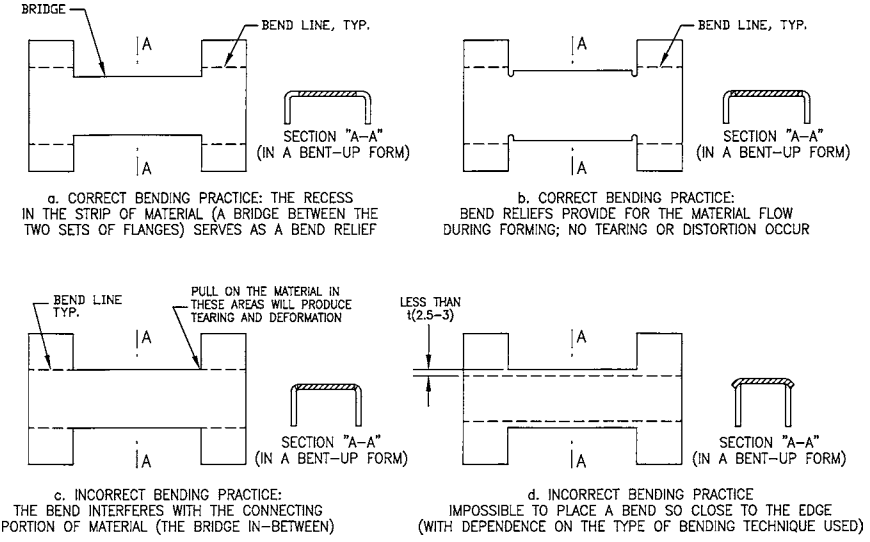
BRIDGE
BEND LINE, TYP.
A
A
SECTION "A–A"
(IN A BENT–UP FORM)
a. CORRECT BENDING PRACTICE: THE RECESS IN THE STRIP OF MATERIAL (A BRIDGE BETWEEN THE TWO SETS OF FLANGES) SERVES AS A BEND RELIEF
BEND LINE, TYP.
A
A
SECTION "A–A"
(IN A BENT–UP FORM)
b. CORRECT BENDING PRACTICE: BEND RELIEFS PROVIDE FOR THE MATERIAL FLOW DURING FORMING; NO TEARING OR DISTORTION OCCUR
BEND LINE TYP.
PULL ON THE MATERIAL IN THESE AREAS WILL PRODUCE TEARING AND DEFORMATION
A
A
SECTION "A–A"
(IN A BENT–UP FORM)
c. INCORRECT BENDING PRACTICE: THE BEND INTERFERES WITH THE CONNECTING PORTION OF MATERIAL (THE BRIDGE IN–BETWEEN)
LESS THAN t(2.5–3)
A
A
SECTION "A–A"
(IN A BENT–UP FORM)
d. INCORRECT BENDING PRACTICE IMPOSSIBLE TO PLACE A BEND SO CLOSE TO THE EDGE (WITH DEPENDENCE ON THE TYPE OF BENDING TECHNIQUE USED)

FIGURE 1-26 Flange-bending examples.

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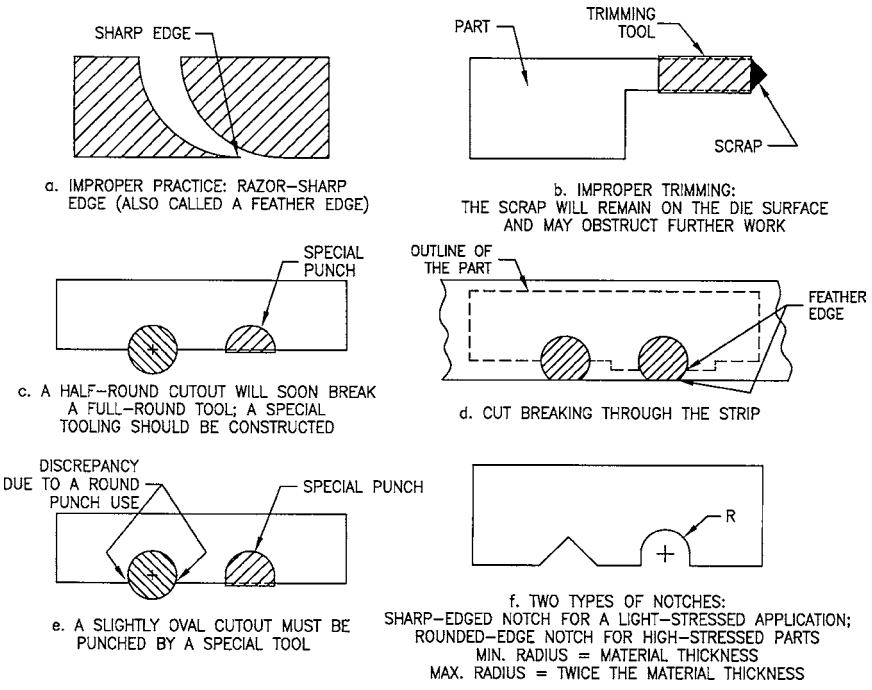
SHARP EDGE
a. IMPROPER PRACTICE: RAZOR–SHARP EDGE (ALSO CALLED A FEATHER EDGE)
PART
TRIMMING TOOL
SCRAP
b. IMPROPER TRIMMING: THE SCRAP WILL REMAIN ON THE DIE SURFACE AND MAY OBSTRUCT FURTHER WORK
SPECIAL PUNCH
c. A HALF–ROUND CUTOUT WILL SOON BREAK A FULL–ROUND TOOL; A SPECIAL TOOLING SHOULD BE CONSTRUCTED
OUTLINE OF THE PART
FEATHER EDGE
d. CUT BREAKING THROUGH THE STRIP
DISCREPANCY DUE TO A ROUND PUNCH USE
SPECIAL PUNCH
e. A SLIGHTLY OVAL CUTOUT MUST BE PUNCHED BY A SPECIAL TOOL
R
f. TWO TYPES OF NOTCHES: SHARP–EDGED NOTCH FOR A LIGHT–STRESSED APPLICATION; ROUNDED–EDGE NOTCH FOR HIGH–STRESSED PARTS
MIN. RADIUS = MATERIAL THICKNESS
MAX. RADIUS = TWICE THE MATERIAL THICKNESS

FIGURE 1-27 Examples of edge trimming.

instead of full round cut, the punch may break through the edge and create featheredge on both sides of the cut (see Fig. 1-27*d*). And even where enough material was left for that purpose, it may be an economically unjustified waste to utilize it just for scrap. In these cases a special-shaped tool is a necessity, which will pay for itself in lesser tool damage, greater consistency of scrap-free production, and diminished impairment to the part and the die as well.

When evaluating the outline of a part, designers should also beware of *phantom bends* (Fig. 1-28), and for that reason a flat layout of every bent-up part should be produced prior to any design work.

Phantom bends are those which appear to be correct on the bent-up drawing, but actually cannot be produced for various reasons. Most often there is not enough material to form the bent-up portions, or a section of the part interferes with another. These flaws are not always obvious from the part's drawing, especially where the product is complex in shape. An accurate flat layout not only provides for spotting these problems beforehand, it also displays the extent of their interference and presents possible solutions.

Additionally, flat layouts are important for a proper assessment of the size of a blank, as shown in Figs. 1-29 and 1-30. Where a part itself may often seem small, its blank may be considerably larger than anticipated. This is most often caused by the size and location of scrap areas, attributable either to the part's shape, or to the method of bending. If the part-forming procedure is not specified on the drawing, manufacturers may feel free to combine bends and seams to suit production practices. These alterations allow for a manipulation of the shape of the blank, shown in Fig. 1-30. By changing the blank outline, while still producing the same formed part, more economical arrangements may be arrived at.

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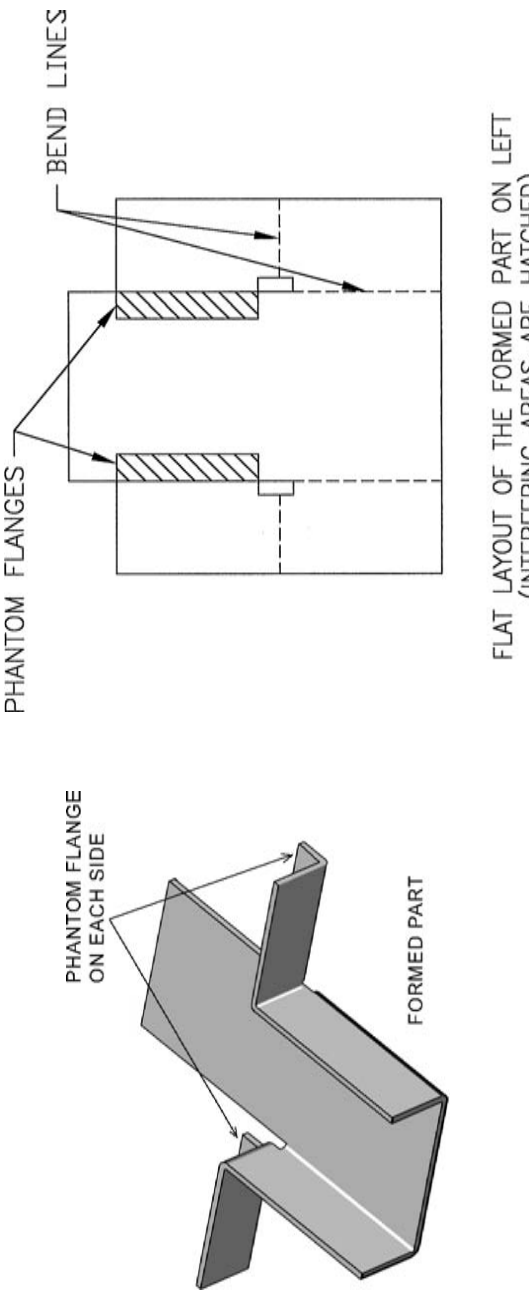

FIGURE 1-28 Example of phantom bends. Flat layout of the formed part on left. Interfering areas are hatched.

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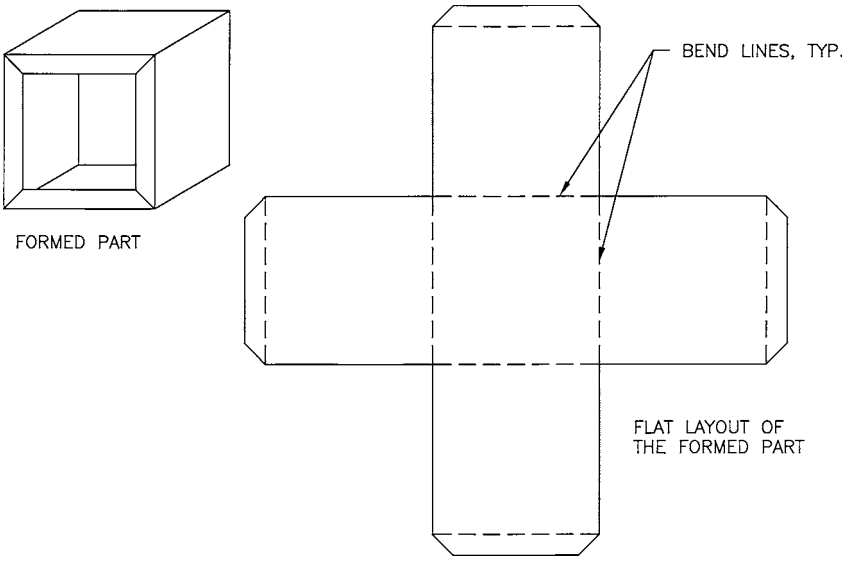

FIGURE 1-29 Formed part and its flat layout.

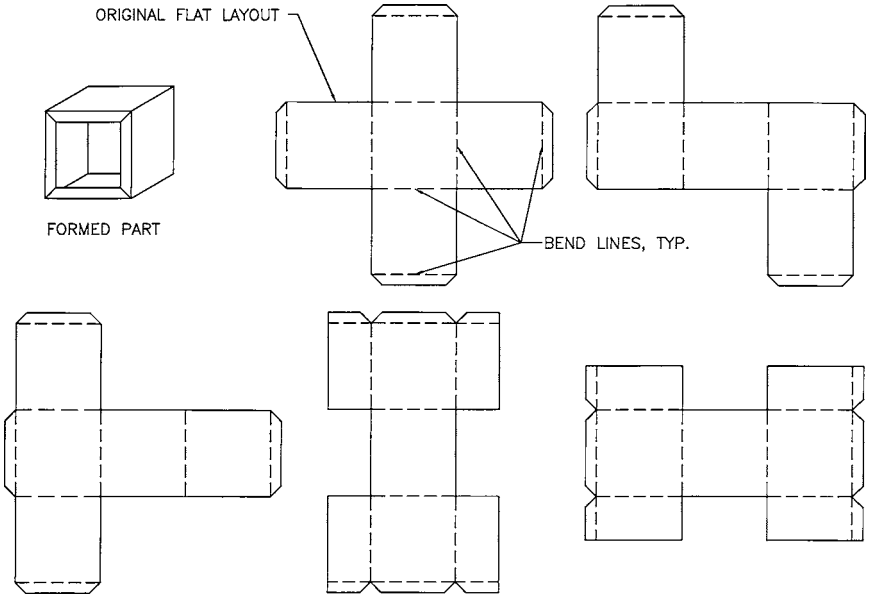

FIGURE 1-30 Flat layout variations.

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However, in sheet-metal stamping, many scrap areas may be decreased, if not minimized, just by rearranging parts on the strip (Fig. 1-31). Naturally, the size of the resulting strip, and consequently the size of the die must be kept in mind in the course of such evaluation.

1-3-1-5 Applicable Tolerance Ranges. Unreasonable tolerancing demands may cause a many good die designs to turn into failures. Tolerance ranges that are too tight or out of ordinary may increase the demands for sharpening of tooling, multiply the need for additional fine-finishing operations, increase the cost of a strip material, and stifle the production floor in many other ways.

What are such *unreasonable tolerancing demands*? These are all those that are impossible to achieve in a die work or a sheet-metal work in general. A ±.005 in. [0.13 mm] tolerance applied to a distance of an opening's center off the edge may be considered one of them. Quite often, it cannot even be measured. After all, how do we determine where the edge starts? Is it at the upper surface of the material, or at the burr side? The burr itself may sometimes amount for the total, if not more, of such tolerance. Is the edge from which we are measuring straight, or is it slightly off the parallel? Where is the hole center? It is certainly

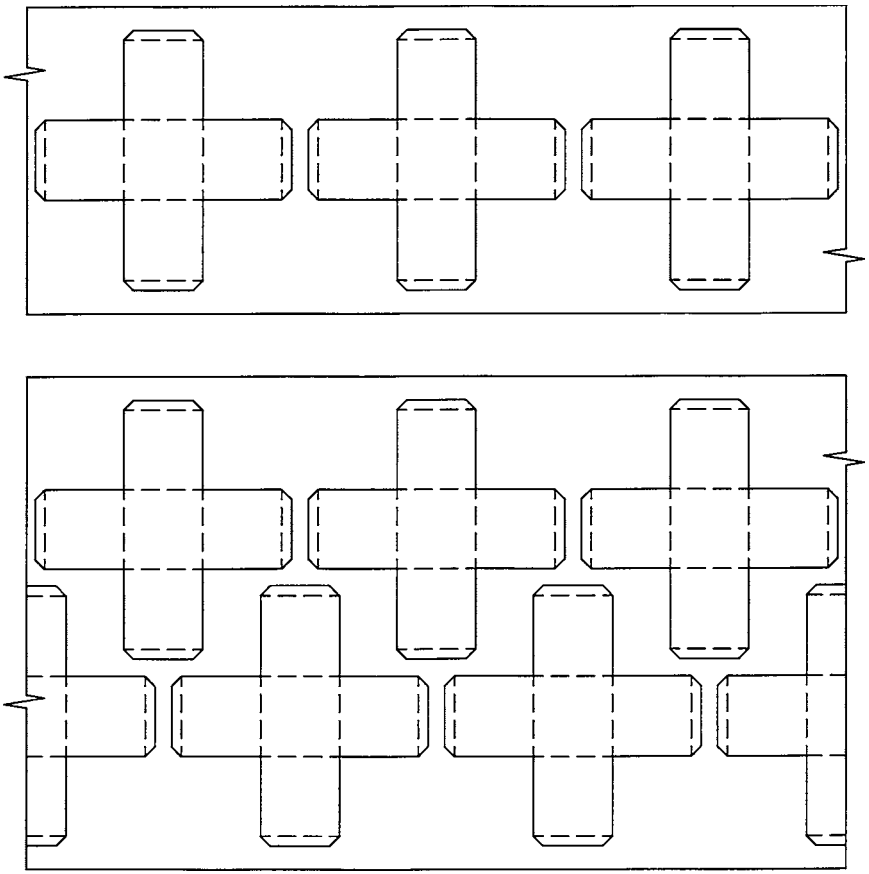

FIGURE 1-31 Two variations of strip layout.

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not firmly specified by a point in the midst of an opening, for which reason it is mostly deduced from the measurable diameter of that hole. Now, how do we know that the hole is completely round? What if it is minutely irregular? What if it is skewed? What if we are picking a burr or a notch instead of hole diameter?

Some may resort to giving the distance off the edge of the part to the edge of the opening, which is an invitation to a host of other problems. What if, for example, the punch is not exactly the size it should be? It will certainly affect the measurement greatly. And if the punch is the correct size, how do we know the tolerance between the punch and die did not affect the hole size or formation of its edge? What if we are not measuring exactly on the center line of the opening but slightly off, few degrees up or down?

These and many other questions may often puzzle designers, quality control inspectors, and production engineers, where the regular die-production problems and challenges are further enhanced by unreasonable tolerancing demands.

Another example can be seen in a ±.005 in. [0.13 mm] between two openings. This is considered a regular tolerance range of most NC turret presses. Dies can do better than that. But what if those openings are spaced 12 in. [305 mm] apart? How would the tolerance range fare at that distance? What kind of temperature is specified for such measurement to take place at? The thermal expansion coefficient of metal material can do wonders when it comes to accuracy.

We may also have a case where a ±.005 in. [0.13 mm] tolerance range is prescribed after the product has been subjected to the welding or brazing process. We all know that these operations can alter the material in many ways. These may cause it to expand, to warp, twist, or otherwise distort. In this case, even a slight expansion, warpage, or twist will instantaneously bring us out of the given tolerance range.

Tolerance ranges are there to help us. They should not be used to act as hindrances. We must bear in mind that more stiff requirements for a hole-to-hole dimensioning may require shaving of that opening, which is an additional operation, an additional station in a progressive die, and an additional cost. We must realize that a very tight tolerance range on a bend in soft metal is useless, if that bend can be further affected by the pressure of bare hand. These and many other tolerance applications must be carefully scrutinized by designers and judged on the basis of their adherence to the two basic manufacturing principles: common sense and work experience.

1-3-1-6 Surface Finish, Flatness, Straightness, and Burr Allowance. As can be deduced from the preceding section, tolerance ranges on flatness, straightness, and burr size vary with application. Where a greater distortion is allowable for one product, it may totally ruin the functionability of another part.

Surface flatness and straightness, as specified by the manufacturer of raw materials, may not always be adequate for our needs. The rule of thumb is, where more than generally obtainable criteria are specified, these can most often be achieved, at an additional cost. Each and every ±.001 in. [0.025 mm] of tightened tolerance range caries along a price tag. If a product is not straight enough, it can be somewhat straightened by sizing, or flattened by grinding. Where openings are too finely dimensioned and toleranced and a burr is inexcusable, holes can be repunched, shaved, or even redrilled/milled. Welds can be ground almost invisible, edges can be sanded absolutely smooth, and parts can be polished to perfection—all that, at a cost.

Surface finish is another aspect that affects the production results extensively. How fine a surface of a product has to be? Is it but cosmetic fineness the designer is seeking, or is it a functional smoothness? Are nicks and scratches allowed on the inner (hidden) surface of the part? How many openings are to be masked prior to painting?

With unpainted products, do we know how many parts can be placed in a barrel before they will become ruined by their own weight and by the shuffle during the transport? Was packaging, designed for transport of sensitive elements properly tested? How about a drop test—is it performed routinely, or is it routinely ignored?

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BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

Products, even where arranged in layers and separated by protective barriers, can still become damaged in transport. Already the fact that one part's sharp edge can dig into the face surface of another, or that parts may be rubbing against each other, bends in nonhardened materials may become further "adjusted"—these little treacheries have to be taken into account long before the first production run is delivered to the customer.

At the same time, where additional packaging requirements arise long after the quote has been submitted to the customer and accepted, these are increasing our own manufacturing expenses. Disposable packaging versus returnable barrels or crates includes a hefty surcharge in the difference between the two. Protective wrapping, "egg crating," or heat shrink packaging adds to the cost. Stacking the parts for packaging and restacking them for placement into shipping containers adds to the cost as well. And to add "insult" to the damage, by excessive handling of products we may further scuff their surfaces, damage the alignment, affect the bends, and cause many additional problems to previously perfect parts.

1-3-2 Functionability Aspects

Another method of evaluating a product is its functionability. To be functional, a part must sustain the anticipated amount of work cycles, while performing all its intended duties without any unusual wear, without excessive need for repairs, without succumbing to rust or corrosion, without significant changes in its outward characteristics, and without causing damage to any other part of the assembly or manufacturing system.

A well-designed, well-manufactured, and well-functioning part must be sturdy enough but not exaggerated in size or weight. It should use the supportive function of its grain structure in places where expected or necessary. It must not become detrimental to the function of surrounding parts or mechanisms and it must not mar the surfaces of adjoining elements (including the hands of the operating personnel) even in the absence of protective means.

If the design calls for a part which may be considered aggressive to its surroundings, be it for its shape, sharp edges or unfinished corners, proper barriers or protective devices should be used in manufacturing, transport, and storage.

Where possible, parts should be designed to allow for stacking. Their size and shape must fit the packaging material freely, without any constraints, yet with no excessive free space left for their movement during transport.

The amount of parts in a shipping container must be well proportioned to their weight, so that the load of the cargo will not cause any damage to the bottom layers of the batch.

Sturdiness of a sheet-metal part is often aided by the inclusion of

1. Beads and ribs (strips)
2. Bosses or buttons
3. Flanges
4. Lightening holes

The first 3 three-dimensional structural enhancements protect the part's surface from deformation, buckling, or so-called *oilcan effect*. They also strengthen the material structure not only by their shape, but also by the cold work of the forming operation. To relieve a part that must be of greater thickness and yet its weight is of concern, lightening holes are used.

1-3-2-1 Beads and Ribs. There are two types of these formations: internal beads and external beads.

Internal Beads. It can be produced either by rubber pad forming, or by a set of matching dies.

In rubber pad forming (Fig. 1-32*a*), the entire surface of sheet-metal strip comes into contact with the rubber pad at the same moment. As the pressure increases and the metal is

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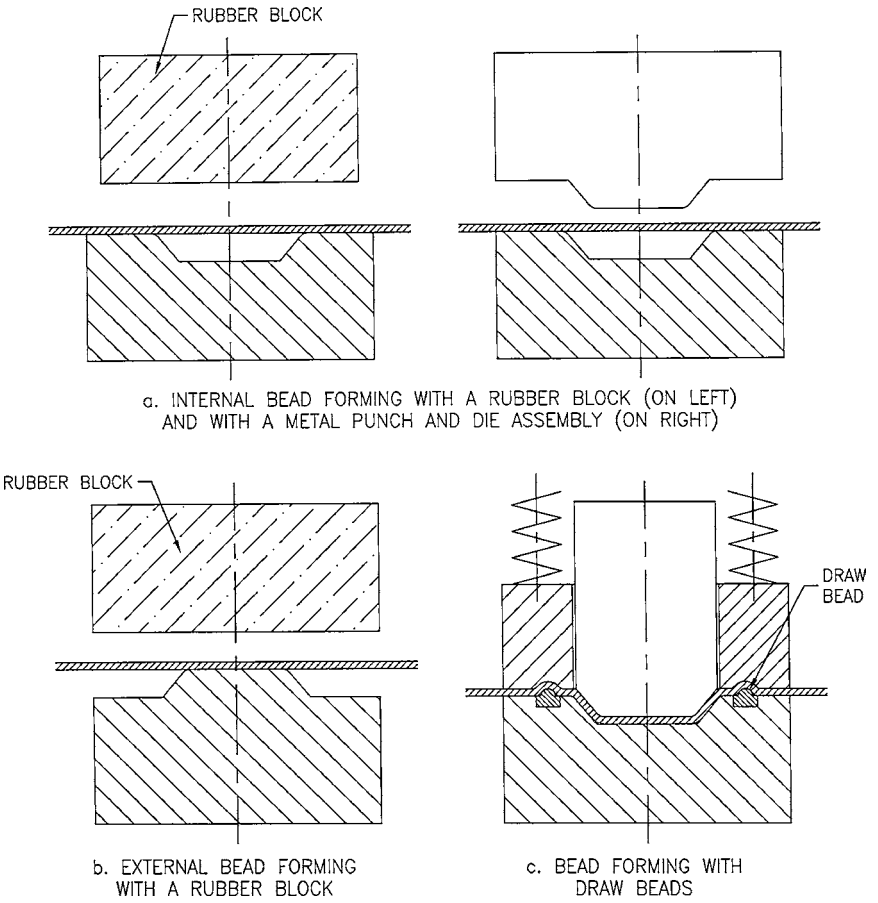
RUBBER BLOCK
a. INTERNAL BEAD FORMING WITH A RUBBER BLOCK (ON LEFT)
AND WITH A METAL PUNCH AND DIE ASSEMBLY (ON RIGHT)
RUBBER BLOCK
DRAW
BEAD
b. EXTERNAL BEAD FORMING
WITH A RUBBER BLOCK
c. BEAD FORMING WITH
DRAW BEADS

FIGURE 1-32 Internal and external bead forming.

forced into the die recess, the surrounding material is already restrained from movement by the pressure of the rubber pad. Therefore the only deforming portion is that of the bead itself, while the surrounding material is not influenced by the metal flow.

With die-forming of internal beads, the outward-protruding punch reaches the material first and starts to form the bead without establishing a firm restraining contact with the remaining material. The material under the punch is stretched and as the tool descends further, it pulls on the surrounding portions of material, possibly distorting it somewhat in the process, with dependence on the depth of the bead.

The maximum possible internal bead depth a (shown later in Figs. 1-34 and 1-35) depends primarily on the width of bead A, standard beads commonly having a ratio of width to depth between 4 and 6, or

$$\frac{A}{a} = 4 \text{ to } 6 \tag{1-1}$$

On large, flat surfaces, beads should be spaced as closely as possible, to give maximum strength to the metal and to avoid large flat areas, which are inherently weak. Between parallel

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beads, the minimum spacing is about 8*a* to allow full bead formation without fracturing the metal. Between a bead and a flange at right angle to the bead, allow 2*a*; between beads at right angles to each other, allow 3*a*; and between a bead and a flange parallel to the bead, allow 5*a*.

External Beads. With external beads, the pressure of the rubber pad is first applied to the top of the bead (see Fig. 1-32*b*). Metal is locked at this point, and with increasing pressure the area between bead strips is stretched until it bottoms on the form block. Deformation being thus spread progressively over a large area, an external bead can be formed considerably deeper than an internal bead of the same curvature. Somewhat disadvantageous is the necessity of a rather large edge radius. Still, the contours of external beads are sharper than those of internal beads and for that reason the external beads are more efficient stiffeners of the two.

Of disadvantage is the wear and tear of the rubber tooling, which is considerable. This naturally drives the cost of any rubber-forming quite high.

Draw Beads. In forming or drawing process, a material-restraining action can be provided by draw beads (Fig. 1-32*c*). These inserts not only secure the material in a given position, they further prevent its wrinkling during forming action.

The disadvantage of this application is the size of the draw radii. The draw radius of the punch should be four times the material thickness and the draw radius of the die still greater. If a smaller set of radii will be used, the material will tear. However, using greater than necessary radii will not aid the manufacturing process either. In such a case, the strip will not be restricted in its movement, and it may flow along with the forming or drawing action, resulting in the formation of wrinkles.

The only way to adapt the final corner radius to the requirements of the print or to those of practicality is to restrike that area of part after forming, with properly sized tooling.

As shown in Fig. 1-33, there are two basic types of draw beads: mold-type draw beads and lock-type beads. Mold-type bead allows for some material movement in the area between the bead itself and the punch; the lock-type bead takes away that possibility.

Shapes. Shapes of beads or ribs can vary from application to application. There are corner-stiffening ribs, reinforcing beads, and hole-reinforcing beads. Figure 1-34 and 1-35 show an example of corner bead design. Locked-in beads are those that end sooner than the edge of the part. These should be always connected with the remaining flat surface by liberal radii.

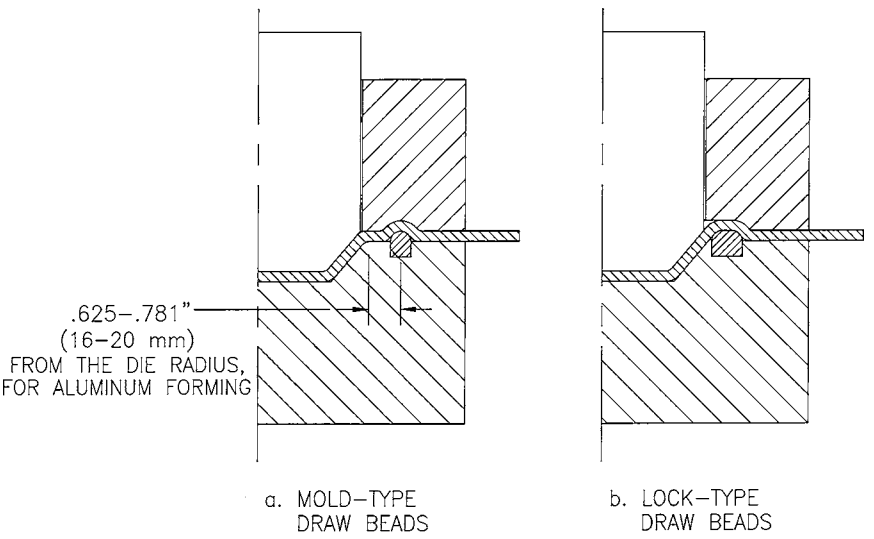

FIGURE 1-33 Draw bead types and recommended distances for their construction.

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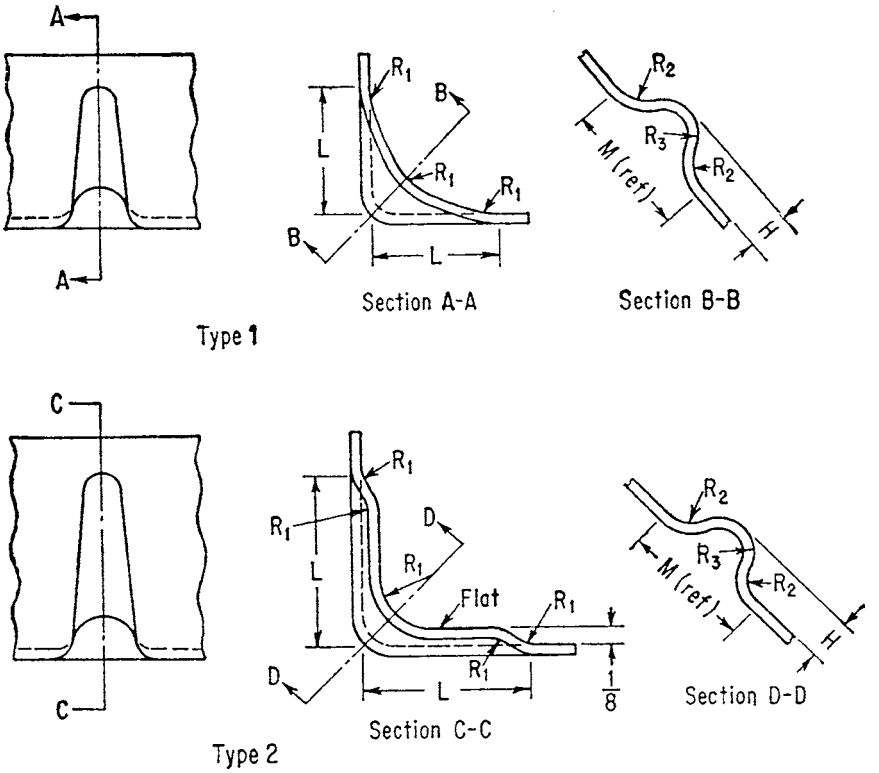

FIGURE 1-34 Corner bead design (*Reprinted with permission from* "Product Engineering Magazine.")

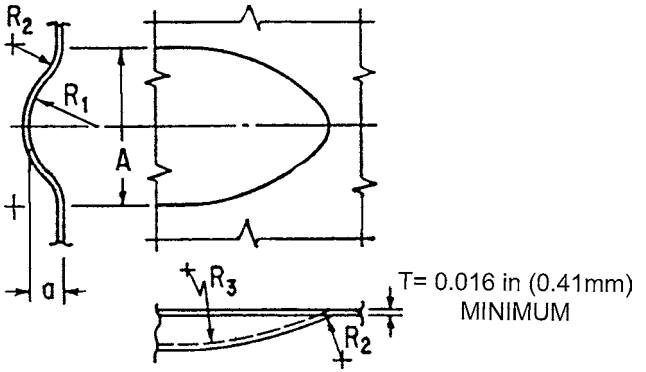

FIGURE 1-35 Bead design. (*Reprinted with permission from* "Product Engineering Magazine.")

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TABLE 1-1 Corner Bead Design Data

Size L	Type	R_1	R_2	R_3	H	M (ref)	Spacing between beads
In inches:							
1/2	1	1/4	23/64	3/16	1/8	23/32	2 1/2
3/4	1	5/16	41/64	17/64	13/64	1 5/32	3
1 1/4	2	11/32	55/64	21/64	17/64	1 1/2	3 1/2
In millimeters:							
12.7	1	6.4	9.1	4.8	3.2	18.3	63.5
19.1	1	7.9	16.3	6.7	5.2	29.4	76.2
31.8	2	8.7	21.8	8.3	6.7	38.1	88.9

Note: The chart refers to Fig. 1-34 .
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A circumferential bulge (Fig. 1-36), a hem, a joggle, or a curl (Fig. 1-37), can all be considered beads, for they provide the part with reinforcing action. A drawn-box can be reinforced by making its sides slightly convex; a container can have a convex bottom or a recessed concave bottom not only to strengthen its construction but to flatten the circumferential area of its base as well.

The bead design data are given in Tables 1-1 and 1-2.

Reinforcing circumferential ribs (Fig. 1-36*a*) are usually formed around openings. Since the ribs are the last to be formed, with the hole already in place, they should be as far away from that opening as possible in order to minimize its distortion.

These beads are actually the size of their radius deep. The radius is dependent on the stock thickness, type of material, and forming pressure as follows:*

For circular ribs

$$R_{\text{in}} = \frac{2(TS)}{P} \tag{1-2a}$$

$$R_{\text{mm}} = (6.894 \times 10^{-3}) \frac{2(TS)}{P} \tag{1-2b}$$

and for elongated ribs

$$R_{\text{in}} = \frac{TS}{P} \tag{1-3a}$$

$$R_{\text{mm}} = (6.894 \times 10^{-3}) \frac{TS}{P} \tag{1-3b}$$

where R = bottom radius, in. or mm
T = material thickness, in. or mm
S = tensile strength, lb/in.^{2} or MPa (N·mm^{-2})
P = forming pressure, lb/in.^{2} or MPa (N·mm^{-2})

*Formulas in this chapter are based on those given in Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from the McGraw-Hill companies.

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TABLE 1-2 Bead Design Data

a		A		R_1		R_2		R_3		T*		$T^{\dagger}$	
in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Low-carbon Steel, Aluminum, Magnesium													
0.05	0.25	0.25	6.4	0.109	2.8	0.070	1.78	0.5	13	0.016	0.4	0.032	0.8
0.10	2.54	0.5	12.7	0.219	5.6	0.140	3.56	1	25	0.025	0.6	0.040	1.0
0.15	3.81	0.75	19.1	0.328	8.3	0.210	5.33	1.5	38	0.032	0.8	0.064	1.6
0.20	5.08	1	25.4	0.438	11.1	0.280	7.11	2	51	0.040	1	0.064	1.6
0.25	6.35	1.25	31.8	0.547	13.9	0.350	8.89	2.5	64	0.051	1.3	0.064	1.6
0.30	7.62	1.5	38.1	0.656	16.7	0.420	10.67	3	76	0.064	1.6	0.064	1.6
0.35	8.89	1.75	44.5	0.766	19.4	0.490	12.45	3.5	89	0.064	1.6	0.064	1.6
0.40	10.16	2	50.8	0.875	22.2	0.560	14.22	4	102	0.064	1.6	0.064	1.6
0.60	15.24	3	76.2	1.313	33.3	0.840	21.34	6	152	0.064	1.6	0.064	1.6
0.80	20.32	4	101.6	1.750	44.5	1.120	28.45	8	203	0.064	1.6	0.064	1.6
1.00	25.40	5	127.0	2.188	55.6	1.400	35.56	10	254	0.064	1.6	0.064	1.6
1.20	30.48	6	152.4	2.625	66.7	1.680	42.67	12	305	0.064	1.6	0.064	1.6
Titanium													
0.38‡	9.7‡	1.33	33.8	0.46	11.7	0.250	6.35	1.12	28			3.88¶	98.6¶
0.38	9.7	1.90	48.3	0.94	23.9	0.250	6.35	1.12	28				
0.50‡	12.7‡	1.75	44.5	0.72	18.3	0.250	6.35	1.5	38			2.50¶	63.5¶
0.50	12.7	2.50	63.5	1.56	39.6	0.250	6.35	1.5	38				
0.70	17.8	3.50	88.9	2.32	58.9	0.250	6.35	2.0	51				
0.88‡	22.4‡	3.08	78.2	1.46	37.1	0.250	6.35	2.52	64			1.76¶	44.7¶
0.88	22.4	4.40	111.8	3.00	76.2	0.250	6.35	3.52	89				
1.12‡	28.4‡	3.92	99.6	2.00	50.8	0.250	6.35	3.0	76			1.26¶	32.0¶
1.12	28.4	5.60	142.2	3.82	97.0	0.250	6.35	3.0	76				

*Maximum thickness for rubber-pad-formed beads on a hydraulic press.
†Maximum thickness for beads formed by punch and die on a mechanical press.
‡Use when edge of bead to edge of sheet does not exceed the dimension shown.
¶Maximum distance between edge of bead and edge of sheet. See Fig. 1-35.
Note: Beads of these proportions may be formed in titanium pure AMS 4901, hot or cold. Further in titanium alloy RE-T-41 and in cold only RE-T-32. In the latter case, the radius R_2 should be 0.312 in. [8.00 mm] for alloy of 0.063 in. [1.60 mm] thickness.
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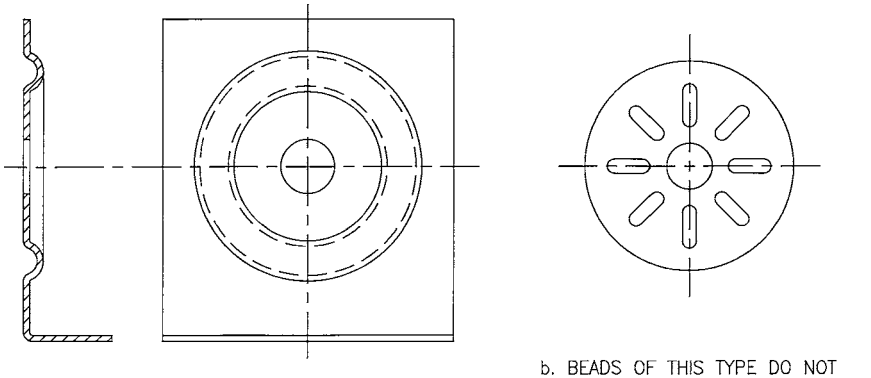
a. REINFORCING CIRCUMFERENTIAL RIBS AROUND A HOLE IN STAMPING
b. BEADS OF THIS TYPE DO NOT OFFER PROTECTION AGAINST BUCKLING OR POPPING OF THE SURFACE UP AND DOWN (i.e. OIL–CAN EFFECT)

FIGURE 1-36 Circumferential ribs in stampings. (*From Frank W. Wilson*, "Die Design Handbook," *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

1-3-2-2 Bosses or Buttons. These are flat-bottomed circular depressions or elevations in sheet (see Fig. 1-38). They are most often used for offsetting purposes, be it for hardware or for other applications. Their sizes and heights with respect to the given material thickness are listed in Table 1-3.

1-3-2-3 Flanges. These can be either straight or curved. Straight flanges are made by simple bending of a portion of sheet-metal material, with no flow of material involved in the process. Curved flanges seem to utilize simple bending technique as well; however, this is accompanied by stretching or compressing action on the material, which induces the material to flow. The material flow is similar to that in drawing or other cold work.

With curved flanges, there is always a certain amount of deformation involved. In convex or shrink flanges (Fig. 1-39*b*), the material of the flange is compressed in order to produce the required shape. In concave or stretched flanges (Fig. 1-39*c*), the material of the flange is elongated. The amount of deformation, when calculated, can be used to determine the exact type of the flange.

$$\% \text{ of deformation} = 100\left(\frac{R_2}{R_1} - 1\right) \tag{1-4}$$

where R_1 is the edge radius before forming, in flat, in. or mm, and R_2 is the edge radius after forming, in. or mm.

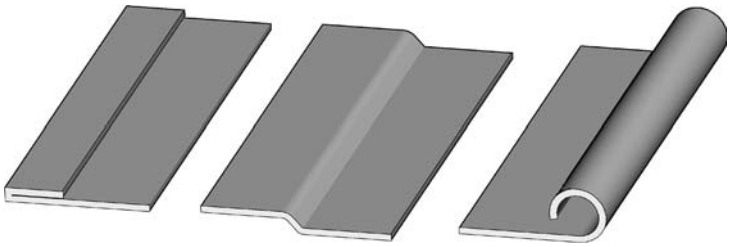

FIGURE 1-37 Other types of forming: a hem, a joggle, and a curl.

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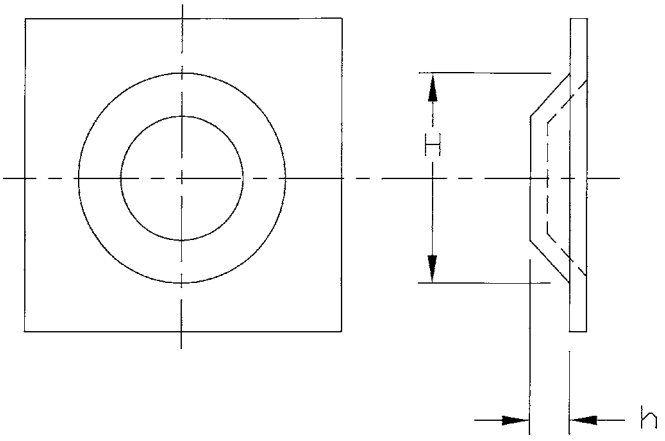

FIGURE 1-38 Round beads or bosses (See Table 1-3 for values).

If the deformation percentage comes out as a positive number, an elongation of material (stretch) is involved. With a negative number, the compression (shrink) is indicated. Table 1-4 gives maximum forming limits.

The amount of setback for all flanges can be determined from Fig. 1-40 by connecting the radius scale at the value R to the thickness scale at the value of T with a straight line. The setback value J is read at the point where this line intersects the horizontal line representing the bevel of the bend.

Flat-pattern flange width Y can be calculated by using the following formula:

$$Y = W - J \tag{1-5}$$

where Y = flange width, in flat, in. or mm
W = formed flange width, in. or mm
J = value of setback, from Fig. 1-40

Dimensioning of stretch, shrink, and special flanges is given in Fig. 1-41. Dimensions for 90° flanges can be determined from Fig. 1-42, along with the percentage of elongation (stretch) or compression (shrink) in the metal of a given flange.

TABLE 1-3 Design Data For Round Beads or Bosses

Height, h		Material thickness		Suggested ratio, H/h
in.	mm	in.	mm	
1/16 (.062)	1.59	.020	0.51	12–20
		.031	0.79	14–24
		.048	1.22	16–26
3/32 (.093)	2.38	.020	0.51	12
		.031	0.79	14
		.048	1.22	16
1/8 (.125)	3.18	.020	0.51	11
		.031	0.79	12
		.048	1.22	13

Note: Use with Fig. 1-38.

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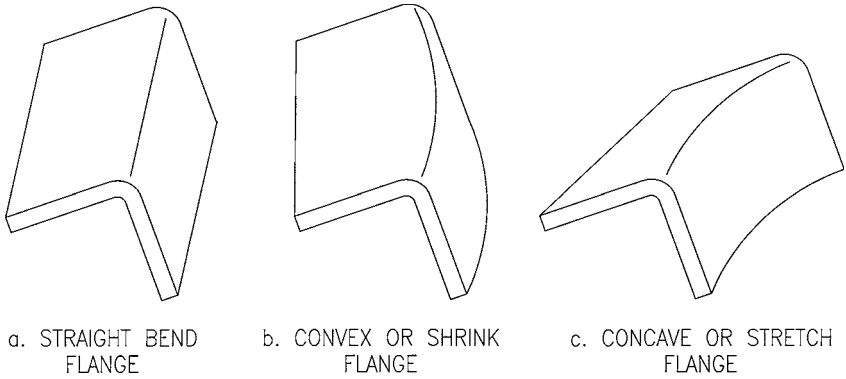

FIGURE 1-39 Three types of sheet-metal flanges.

Connect the flange width value Y to the amount of compression (shrink) with a straight line. Where this line crosses the mold line radius graph, that value is applicable to the given problem.

Dimensions for open or closed flanges can be determined from Fig. 1-43; the method for the chart's use is similar to that described above.

The flange width W or the projected flange width H can be determined from the lower scale. The approximate deformation of the free edge of curved flanges, percentagewise, is determined on the upper scale.

Permissible strain in stretched flanges depends on the edge condition of the metal, flange width (from Fig. 1-41), and method of forming. For 90° flanges, this value may be approximated by using the following formula

$$e = \frac{W}{R_2} \tag{1-6}$$

TABLE 1-4 Maximum Forming Limits for Flanges

	Stretch flanges (Elongation)		Shrink flanges (Compression)	
Material type	Rubber tooling, %	Solid die, %	Rubber tooling, %	Solid die, %
Aluminum 3003-O	20	30	5	40
Aluminum 3003-T	5	8	3	10
Aluminum 5052-O	20	25	5	35
Aluminum 5052-T	5	8	3	12
Aluminum 6061-O	21	22	8	35
Aluminum 6061-T	5	10	2	10
Aluminum 7075-O	10	18	3	30
Aluminum 7075-T	0	0	0	0
Steel 1010	–	38	–	10
Steel 1020	–	22	–	10

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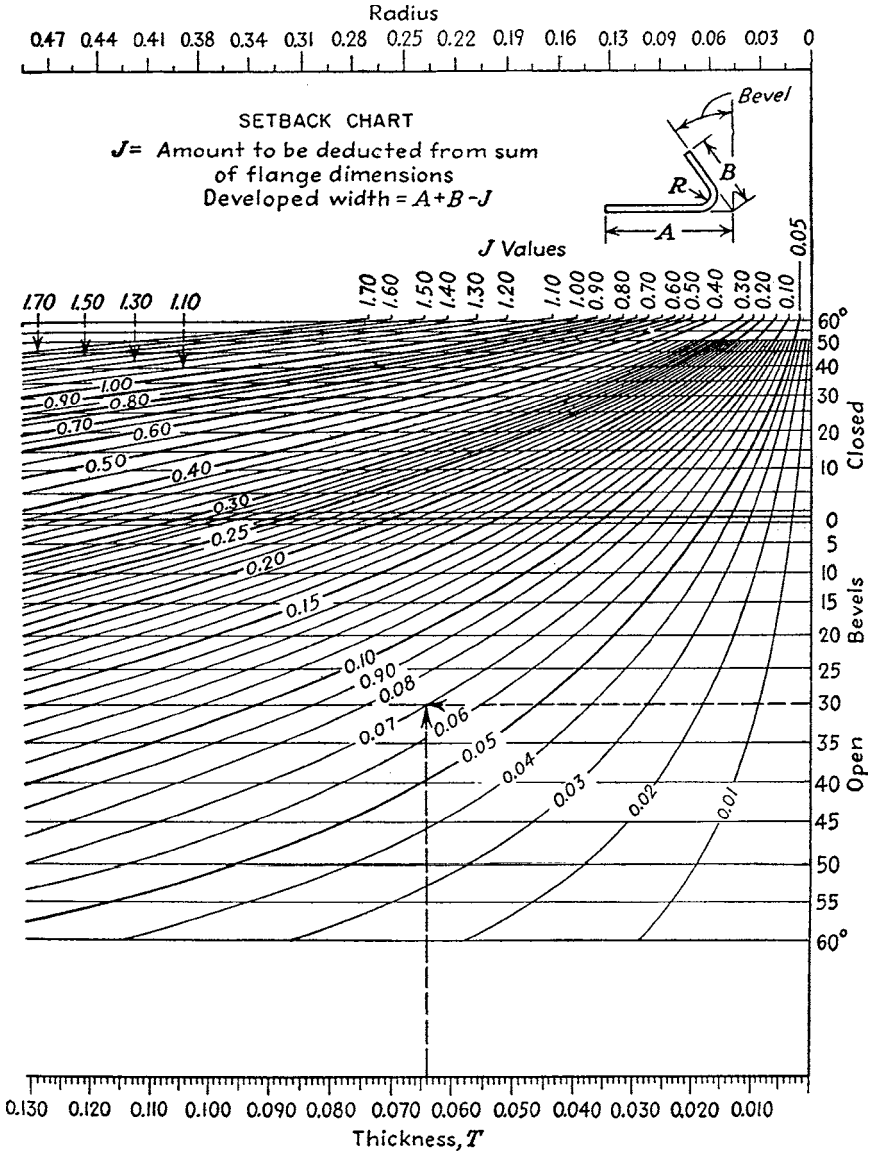

FIGURE 1-40 Setback chart. (*From Frank W. Wilson*, "Die Design Handbook," *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

where e = elongation (strain) factor at free edge of flange (see later)
W = flange width, in. or mm
R_2 = contour radius of bent-up flange, in. or mm

Values for e. For 2024-0, -T3, and -T4 aluminum 90° flanges, 0.10 is a safe value for e where edges are smooth; 0.06 is a safe value for sheared edges. A larger degree of stretch

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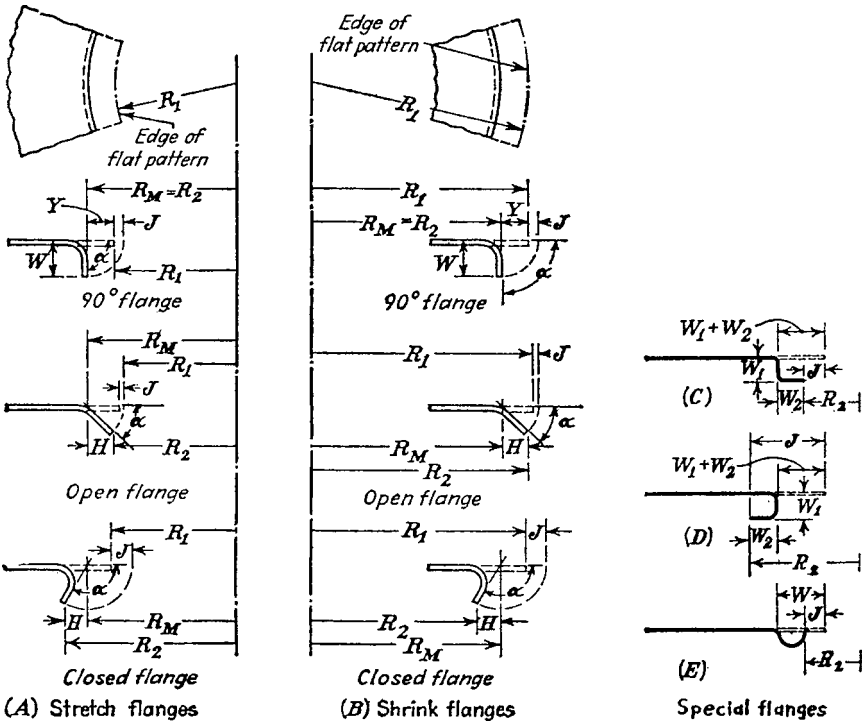

FIGURE 1-41 Dimensioning of flanges: (*a*) for stretch flanges; (*b*) for shrink flanges; (*c*), (*d*), and (*e*) for special flanges. For 90° flanges use Fig. 1-42. For other flanges, use Fig. 1-43. (*From Frank W. Wilson*, "Die Design Handbook," *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

occurs where contour radius R_2 is small or where the stretch flange is adjacent to a shrink flange.

Equation (1-6) for 90° stretch flanges also applies to 90° shrink flanges. Here, however, the metal is in compression, and the sheet must be supported against "buckling" or "wrinkling." With rubber forming, there is practically no support against buckling, and only slight shrinking can be accomplished, so that rubber forming is limited to very large flange radii or very narrow widths.

For 2024-0 aluminum, without subsequent rework, shrink is limited to not over 2 or 3 percent; for 2024-T3 and -T4, shrink is limited to 0.5 percent.

U.S. Air Force specifications indicate that there is danger of cracking when elongation exceeds 12 percent in 2 in. [50 mm]. Therefore, for safety, $e = 0.12$, and

$$\frac{R_2 - W}{R_2} = 0.88 \tag{1-7a}$$

For open flanges (i.e., angles smaller than 90° see Fig. 1-41) the formula is

$$e = \frac{W(1 - \cos\alpha)}{R_2} \tag{1-7b}$$

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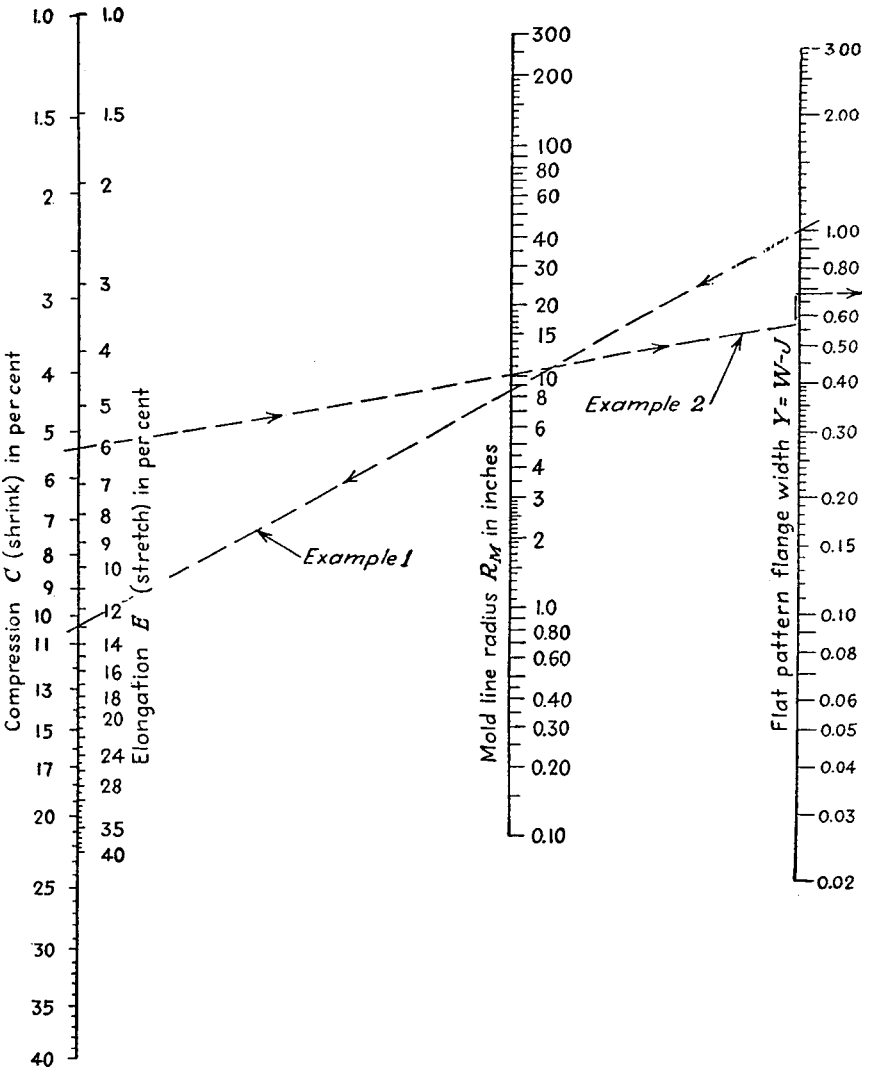
Compression C (shrink) in per cent
Elongation E (stretch) in per cent
Mold line radius R_M in inches
Flat pattern flange width $Y = W - J$
Example 1
Example 2

FIGURE 1-42 Chart for calculating 90° flange width and percentage of deformation. (*From Frank W. Wilson*, "Die Design Handbook," *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

Values of e for some other shaped flanges are as follows:

For flanges in Fig. 1-41*c*,

$$e = \frac{W_1}{R_2} \tag{1-7c}$$

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For flanges in Fig. 1-41*d*,

$$e = \frac{W_1 + 2W_2}{R_2} \tag{1-7d}$$

For flanges in Fig. 1-41*e*,

$$e = \frac{J}{R_2} \tag{1-7e}$$

Cold forming changes the mechanical properties of carbon steel strip and produces certain useful combinations of hardness, strength, stiffness, ductility, and other characteristics. Temper numbers indicate degrees of strength, hardness, and ductility produced in cold-rolled carbon steel strip. These temper numbers are associated with the ability of each temper to withstand certain degrees of cold forming.

The No. 1 temper is not suited for cold forming; temper Nos. 4 and 5 are used for production of parts that involve difficult forming or drawing operations.

1-3-2-4 Lightening Holes. These can be flanged in annealed aluminum alloys up to 0.125 in. [3.18 mm] thick and in heat-treated 2024 aluminum up to 0.064 in. [1.63 mm] thick.

Austenitic stainless steel up to 0.060 in. [1.52 mm] can be formed with external hole flanges and up to 0.050 in. [1.27 mm] thick with internal flanges. The quarter-hard stainless steel up to 0.040 in. [1.02 mm] thick can be externally flanged, and internally flanged up to 0.030 in. [0.76 mm] thick.

Rubber-sheared lightening hole minimum diameters, in relation to aluminum alloy thicknesses, are shown in Table 1-5.

1-3-3 Forming Limitations

It is often difficult, with so many variables at stake, to guess what pitfalls the forming process will generate. Forming can turn a perfectly pierced, embossed, and blanked part into pitiful reject, eating into the company's scrap allowance and diminishing profits. Where the edges of the part are almost invisibly splitting after blanking, large cracks and tears may emerge during forming. Heating of the part, or so-called *torch annealing*, may not always help. And generally advocated "laser it" approach may actually ruin the part altogether.

A laser-cut part has to put up with a molten stage around its edges, which is caused by the cutting process that depends on the speed of the tool and other variables. It will additionally be disadvantaged by the difference in the material grain after cooling of the previously heated areas and subsequent hardening of the surface of the cut and its immediate vicinity. Cracks and tears in the near proximity of laser cuts, especially where the laser "picked up" the path along the part's edge, are often observed.

Lately, computerized simulating tools began to emerge. There were *finite element analysis* (FEA) packages developed for major three-dimensional (3D) solid modelers, with some FEA's as standalones. Many of these are quite user friendly and some are remarkably fast for the amount of operations/calculations they must perform.

When evaluating a 3D analysis software, or perhaps any other software for that purpose, always try to have your own part, no matter how simple, modeled and analyzed right on the spot. This may help to ascertain the length of time and the amount of effort that particular software demands for an input of the information and for producing the results needed. Too many software packages nowadays can generate a so-called "movie," which is a recording of the process, a sort of a "macro," where only the changes on the screen are recorded and all the in-between mouse-clicks, "Enters," keyboard hammering and frustrated hesitation, or waiting are weeded out.

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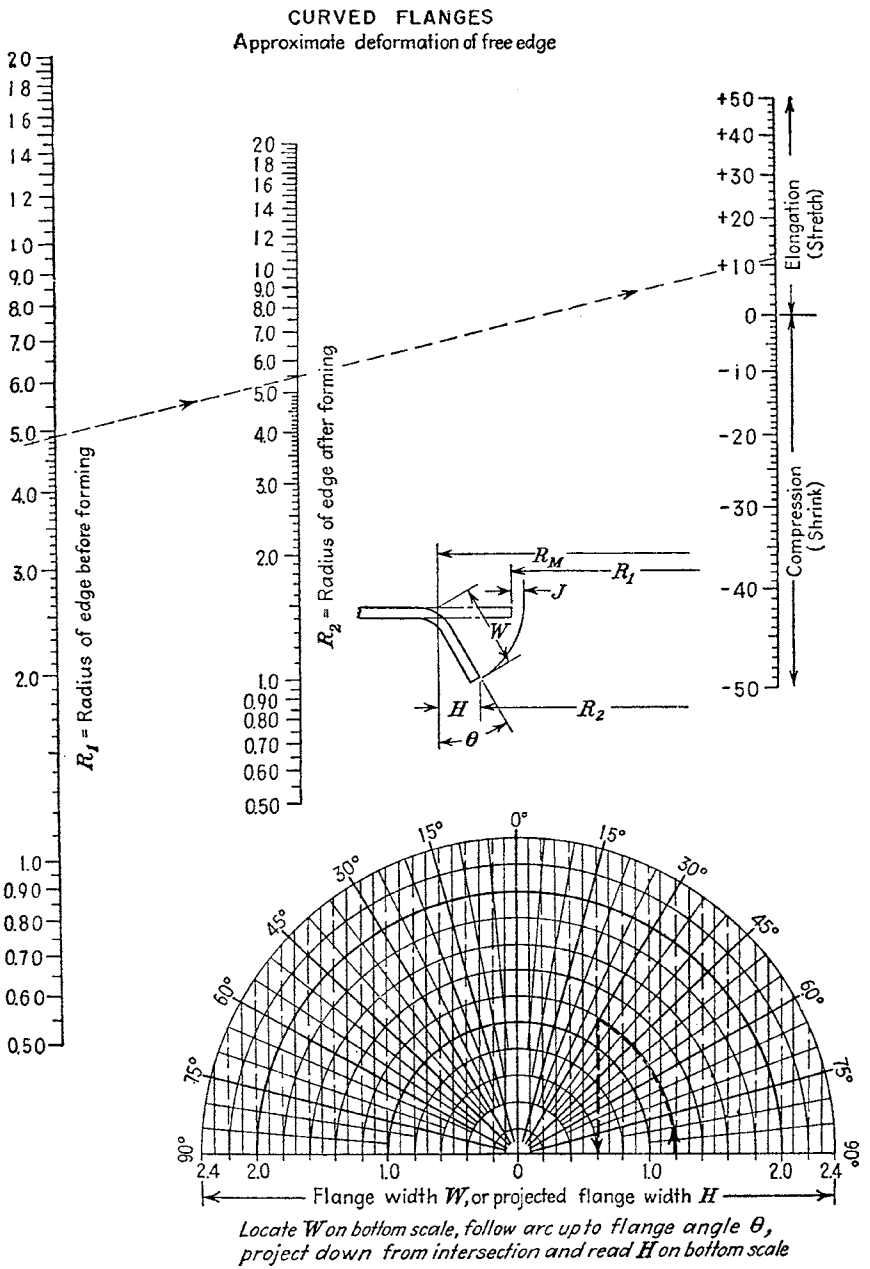

FIGURE 1-43 Chart for calculating widths of open or closed flanges. (*From Frank W. Wilson*, "Die Design Handbook," *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

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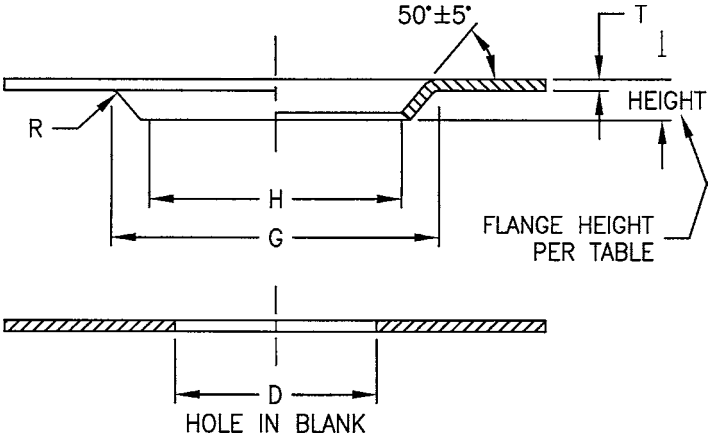
TABLE 1-5 Lightening Holes for 35° Flange*



D		*H*		*G*		*T*		*R*	
in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Flange height 0.125 in. (3.2 mm)									
0.445	11.30	0.812	20.62	1.223	31.06	0.020–0.040	0.51–1.02	0.187	4.75
0.400	10.16			1.212	30.78	0.051–0.072	1.30–1.83	0.250	6.35
0.570	14.48	0.938	23.83	1.348	34.24	0.020–0.040	0.51–1.02	0.187	4.75
0.525	13.34			1.337	33.96	0.051–0.072	1.30–1.83	0.250	6.35
0.695	17.65	1.062	26.97	1.473	37.41	0.020–0.040	0.51–1.02	0.187	4.75
0.650	16.51			1.462	37.13	0.051–0.072	1.30–1.83	0.250	6.35
0.820	20.83	1.188	30.18	1.598	40.59	0.020–0.040	0.51–1.02	0.187	4.75
0.775	19.69			1.587	40.31	0.051–0.072	1.30–1.83	0.250	6.35
Flange height 0.156 in. (4.0 mm)									
0.900	22.86	1.312	33.32	1.800	45.72	0.020–0.040	0.51–1.02	0.187	4.75
0.852	21.64			1.791	45.49	0.051–0.072	1.30–1.83	0.250	6.35
1.150	29.21	1.562	39.67	2.050	52.07	0.020–0.040	0.51–1.02	0.187	4.75
1.082	27.48			2.041	51.84	0.051–0.072	1.30–1.83	0.250	6.35
1.276	32.41	1.688	42.88	2.175	55.25	0.020–0.040	0.51–1.02	0.187	4.75
1.208	30.68			2.166	55.02	0.051–0.072	1.30–1.83	0.250	6.35
1.400	35.56	1.812	46.02	2.300	58.42	0.020–0.040	0.51–1.02	0.187	4.75
1.332	33.83			2.294	58.27	0.051–0.072	1.30–1.83	0.250	6.35
Flange height 0.187 in. (4.7 mm)									
1.606	40.79	2.062	52.37	2.625	66.68	0.020–0.040	0.51–1.02	0.187	4.75
1.543	39.19			2.617	66.47	0.051–0.072	1.30–1.83	0.250	6.35
1.490	37.85			2.611	66.32	0.081–0.102	2.06–2.59	0.312	7.92
1.856	47.14			2.875	73.03	0.020–0.040	0.51–1.02	0.187	4.75
1.793	45.54	2.312	58.72	2.867	72.82	0.051–0.072	1.30–1.83	0.250	6.35
1.740	44.20			2.861	72.67	0.081–0.102	2.06–2.59	0.312	7.92
1.982	50.34			3.000	76.20	0.020–0.040	0.51–1.02	0.187	4.75

(*Continued*)

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TABLE 1-5 Lightening Holes for 35° Flange (*Continued*)

Flange height 0.187 in. (4.7 mm)									
D		*H*		*G*		*T*		*R*	
in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
1.919	48.74	2.438	61.93	2.992	76.00	0.051–0.072	1.30–1.83	0.250	6.35
1.866	47.40			2.987	75.87	0.081–0.102	2.06–2.59	0.312	7.92
2.106	53.49			3.125	79.38	0.020–0.040	0.51–1.02	0.187	4.75
2.043	51.89	2.562	65.07	3.117	79.17	0.051–0.072	1.30–1.83	0.250	6.35
1.990	50.55			3.111	79.02	0.081–0.102	2.06–2.59	0.312	7.92
2.356	59.84			3.375	85.73	0.020–0.040	0.51–1.02	0.187	4.75
2.293	58.24	2.812	71.42	3.367	85.52	0.051–0.072	1.30–1.83	0.250	6.35
2.240	56.90			3.361	85.37	0.081–0.102	2.06–2.59	0.312	7.92
2.606	66.19			3.625	92.08	0.020–0.040	0.51–1.02	0.187	4.75
2.543	64.59	3.062	77.77	3.617	91.87	0.051–0.072	1.30–1.83	0.250	6.35
2.490	63.25			3.611	91.72	0.081–0.102	2.06–2.59	0.312	7.92
2.856	72.54			3.875	98.43	0.020–0.040	0.51–1.02	0.187	4.75
2.793	70.94	3.312	84.12	3.867	98.22	0.051–0.072	1.30–1.83	0.250	6.35
2.740	69.60			3.861	98.07	0.081–0.102	2.06–2.59	0.312	7.92
3.106	78.89			4.125	104.78	0.020–0.040	0.51–1.02	0.187	4.75
3.043	77.29	3.562	90.47	4.117	104.57	0.051–0.072	1.30–1.83	0.250	6.35
2.990	75.95			4.111	104.42	0.081–0.102	2.06–2.59	0.312	7.92
3.356	85.24			4.375	111.13	0.020–0.040	0.51–1.02	0.187	4.75
3.293	83.64	3.812	96.82	4.367	110.92	0.051–0.072	1.30–1.83	0.250	6.35
3.240	82.30			4.361	110.77	0.081–0.102	2.06–2.59	0.312	7.92
3.606	91.59			4.625	117.48	0.020–0.040	0.51–1.02	0.187	4.75
3.542	89.97	4.062	103.18	4.617	117.27	0.051–0.072	1.30–1.83	0.250	6.35
3.490	88.65			4.611	117.12	0.081–0.102	2.06–2.59	0.312	7.92
3.856	97.94			4.875	123.83	0.020–0.040	0.51–1.02	0.187	4.75
3.793	96.34	4.312	109.53	4.867	123.62	0.051–0.072	1.30–1.83	0.250	6.35
3.740	95.00			4.861	123.47	0.081–0.102	2.06–2.59	0.312	7.92

*These lightening holes may be formed in 5052-H32, 6061-T, 2024-T, 2014-T, R-301-T, and 7075-T aluminum alloy and AMC52SO and FS-Ia magnesium alloy or any softer condition of any of these alloys.

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Unfortunately, in die production, as well as in any other production, there may always be some parts that are not acceptable and which are going to be rejected. The only way to guard against large amounts of defective parts in the absence of a 3D analysis software is by testing every theory and every calculation out there, on the factory floor. In fact, in critical areas, testing of formulas such as calculations of bend relieves, or the blank size development of a drawn shell, must definitely be performed using the material allotted to production of that part. Oftentimes, the tools to be used in production can be utilized for testing purposes while being groomed to size during the process.

These precautions are absolutely necessary in order to ensure that there will be no unknown or unpredictable variables affecting the results of the die operation in production and that rejects will not be streaming out of the press *en masse*.

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Some of these hard-to-predict outside influences, constraints, or enhancements include but are not limited to:

- Condition of the cutting, forming, or drawing surfaces
- Presence or absence of lubricants and their composition and suitability
- Hardness of the material being fabricated
- Variation in thickness of sheet-metal material
- Clearance between the cutting, forming, and drawing punch and die
- Spring pressure applied to the pad(s)
- Alignment between the segments of the die assembly
- Ram force and speed

Most of these points are hardly accountable for in a majority of calculations. Actually, there is no way to implement them at all, for the situation will certainly change from one production run to another. For these reasons, the only safe way to proceed is to verify all applicable theoretical results and assumptions out there on the factory floor while being aware of the possibility that one coil can have a different hardness or thickness than the other, watching for surprises created by spring breakage, and guarding the alignment of the die and that of the press.

1-3-4 Control of Close-Toleranced Dimensions

The control of dimensions in die work is still unequalled by other manufacturing processes. Already the fact that a fast-moving strip can be quickly and precisely positioned with the aid of pilots, stops, guides, and other locating elements just before the press comes down, speaks volumes about productivity and effectiveness. The possibility of staging various operations so that one does not affect the other, the wide range of operations that can be performed in a die, the versatility of this tooling approach are just few among many advantages the metal-stamping field presents.

For example, Fig. 1-44 shows a group of closely-spaced *b* openings, serving as a starting point for some rather accurate dimensioning. The spacing between the groups would be jeopardized if a wrong sequence of die work were used. This is because such closely spaced piercing produces a distortion of the material structure, which results in its expansion in that particular area, often to the point of bulging above the remaining surface. This condition can be controlled to a degree with

- Specially shaped punches
- Special cutting conditions
- Staggered cutting

All these techniques are discussed in detail later. At this point, the sequence of operations and their disbursement in a single progressive die will be discussed. Method No. 1 utilizes the following scenario:

1. Pierce the cluster of small *b* openings by staggering the cuts as shown (two stations, each with a special cluster-punch needed)
2. Pilot on the two opposite holes, *c1* and *c2* for further strip advancement
3. Flatten the part in the die if needed or if advantageous
4. Pierce the two large holes, *a1* and *a3*, both sides
5. Pierce the middle large hole, *a2*, both sides

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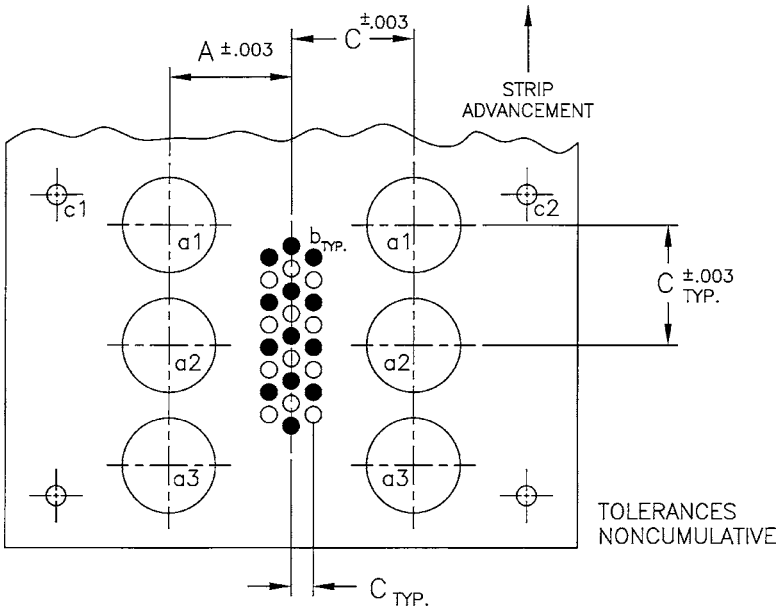

FIGURE 1-44 Accurate piercing through work-sequence adaptation.

This sequence of operations should place the *a* holes into a reasonably exact distance off the center of the middle row of *b* holes.

If the punching was to be reversed and the large *a* holes were punched first, this by itself may have created enough stress-related movement within the material that the ±0.003 in. (0.08 mm) tolerance range will be out of question.

Flattening the part, even though recommended, cannot always be achieved. First of all, we do not know how much the part will bulge after such intense piercing, and therefore we often cannot produce such an arrangement to surely remedy the situation. After all, the results may vary from strip to strip with dependence on the hardness and the thickness of material.

Still another way to produce the hole pattern shown in Fig. 1-44 at a slightly greater cost is presented in the Method No. 2:

1. Pierce the cluster of small *b* openings with a special cluster punch, all holes in one hit. However, the diametral size of each opening must be slightly smaller than that which is needed.
2. Pilot on the two opposite holes, *c1* and *c2* for further strip advance.
3. Pierce all three *a* holes (both sides), all of them smaller than they should be.
4. Repierce the cluster of *b* holes with the correct size punch and die.
5. Repierce the *a* holes (both sides) with the correct size punch and die.

What will happen during Method no. 2 piercing is, the first cutting sequence will create stresses in the material, which will certainly bulge and perhaps even distort. But the second cutting sequence will remove these stressed sections located around each hole. After these small areas of congested material will be removed, the part will flatten itself almost miraculously, and a flat and accurate piece will emerge from the die.

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Unfortunately, this method cannot always be used in die work, as such double punching may prove too cost-intensive.

As with all die work, the sequence of operations to produce a part as shown in Fig. 1-45 should be planned with the overall picture of the final outcome in mind. In Fig. 1-45*a* the bent-up flange's distance off the hole is not controlled, while in Fig. 1-45*b* the same flange has a definite dimensional importance for the hole. The sequence of operations to produce the part shown in Fig. 1-45*a*, should be somewhat as follows:

1. Pierce the holes *b* and *a*
2. Cut the flange relief
3. Bend the flange

The sequence of the piercing may be reversed (first the flange relief, followed by *a* and *b* holes), but the forming should be the last.

To produce the part from Fig. 1-45*b*, the operations must be oriented around the flange, which may need to be produced first:

1. Cut the flange relief
2. Bend the flange
3. Bank off the edge of flange and pierce holes *a* and *b*

The reason for this part's altered sequence of operations is the bending, which is hardly as accurate as piercing. To locate the openings off the flange in flat is sometimes risky, since the flange may or may not be exactly where it is expected to appear. The grain and

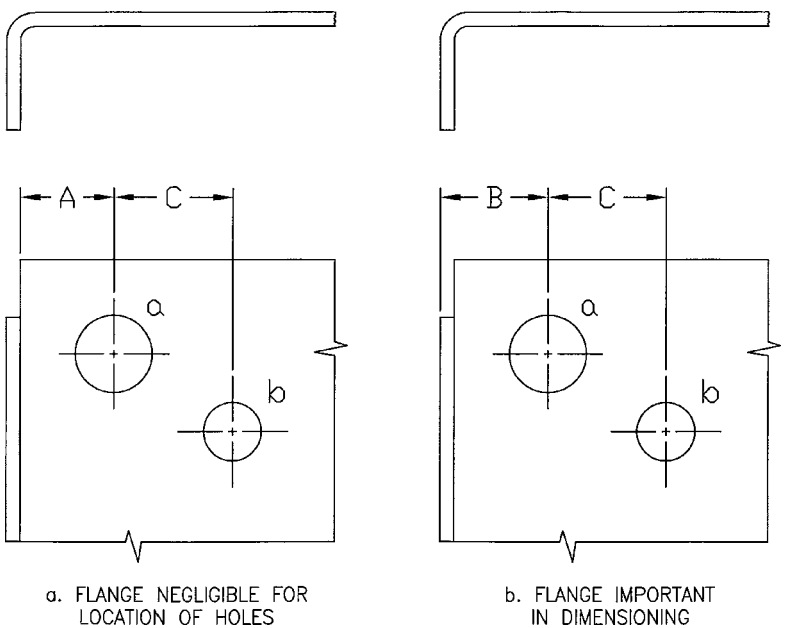

FIGURE 1-45 Dimensions and their control.

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hardness of material, the condition of tooling, and the variation in material thickness, all have a tremendous influence on the distance *B* and subsequently distance *C* in the figure. Therefore, to play it safe, first produce the flange, bank off its edge (outer or inner, whatever is appropriate), and produce the remaining work on the part.

Of course, it is much easier and more economical to pierce all holes in flat and bend the part afterwards, which is a preferred method of fabrication throughout the sheet-metal industry. However, where the bend or bends are more complex, dimensions more accurately toleranced, and where the thickness and condition of material may further complicate the results, often bending first, followed by piercing, is advisable.

A partially bent-up part from Fig. 1-46 is quite another challenge yet. Here the high rectangular boss draws so much material from the strip that all three edges cave in, as shown in the areas marked *A* and *B*. Since a small bend was to be produced in the *A* section later on (see Fig. 1-47), the straight line of the cut was of essence. The die sequence already being in place (Fig. 1-48), there was no chance of switching the cutoff operation to the end.

As the distortion of the part's sides (areas *B*) did not matter to the customer, the die designer concentrated on the area *A* only where a previously straight cut was replaced with a rounded arc (see Fig. 1-49). This way the extra material thus added to the part in flat could be used up for the formation of the rectangular boss, and the final product with its *A* flange straight, is shown in Fig. 1-50.

Naturally, any similarly courageous alterations of the part must be substantiated by adequate testing, for we all know that mistakes in steel are very costly.

Drawn parts are but another challenge for an eager die designer. The changes that can be produced in a part by the drawing process are often mind-boggling.

In Fig. 1-51, there are four *a* openings located on the flange of the drawn part. From the previous text and illustrations, it can be assessed that these holes would be impossible to pierce before the drawing sequence is done. Such assumption is correct and the progression of work should be adjusted accordingly:

1. Preblank the part, leaving it attached to the strip by small bridges.
2. Draw the cup shape.
3. Pierce the four small holes *a.*
4. Blank the outline.

Such logical evaluation of each given problem must be based on an accurate flat layout of the part, and that is usually all the help die designers need. Slowly, sequence after sequence, they should evaluate the information on the drawing, look for hidden obstacles, read every little line, and follow up on all the cuts and cross-sections, before they resort to sketching the actual strip layout. If the part is too complex, they should break it into small areas and evaluate one after another.

Often it may prove helpful to cut the flat layout out of a piece of paper and demonstrate its progression through the die, adding all bending operations by folding it where appropriate and observing the influence on the part's shape and size. Today, with the widespread use of *computer aided design* (CAD) programs, this can easily be simulated on the screen with much greater accuracy and maneuverability.

An accurate flat layout is a gem of information. To produce it, the designer must carefully follow the drawing of the part and omit no information contained on it. The drawing-reading process is complex and involved, and generally, the word "read" should be replaced by "study." All drawings should be carefully studied, screened for information they contain, with follow up on all the coded data, such as specification numbers, coded finish markings, and other procedures that product designers include on them. Often a code consisting of three letters and two alphabetic symbols may be used in lieu of specification several pages long.

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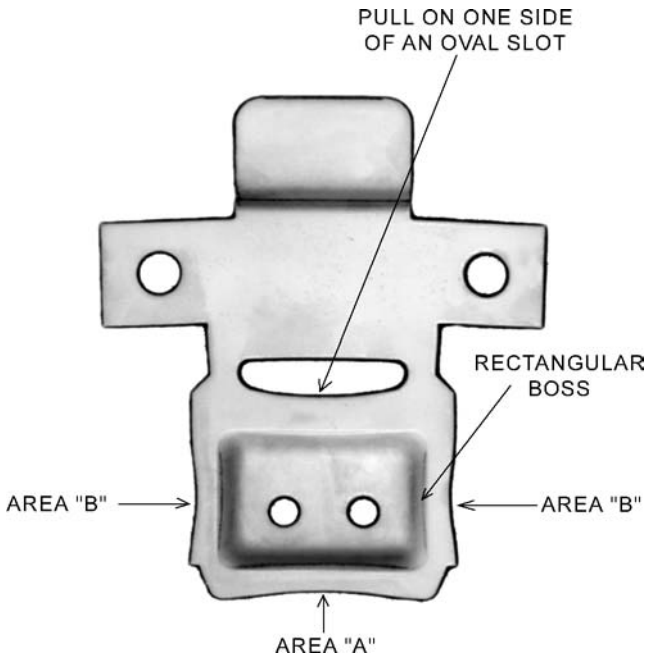

FIGURE 1-46 3000 Series Bottom Clip for Englert T-Seam™ Roof Panel System. Caved-in areas due to forming. (*Reprinted with permission from Englert Inc., Perth Amboy, NJ. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

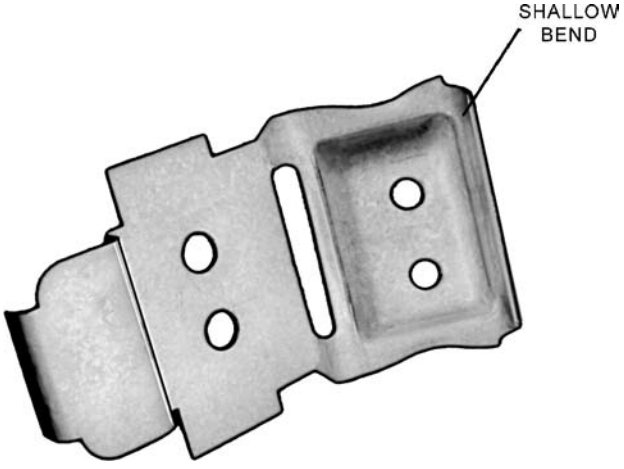

FIGURE 1-47 Partially bent-up part. (*Reprinted with permission from Englert Inc., Perth Amboy, NJ. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

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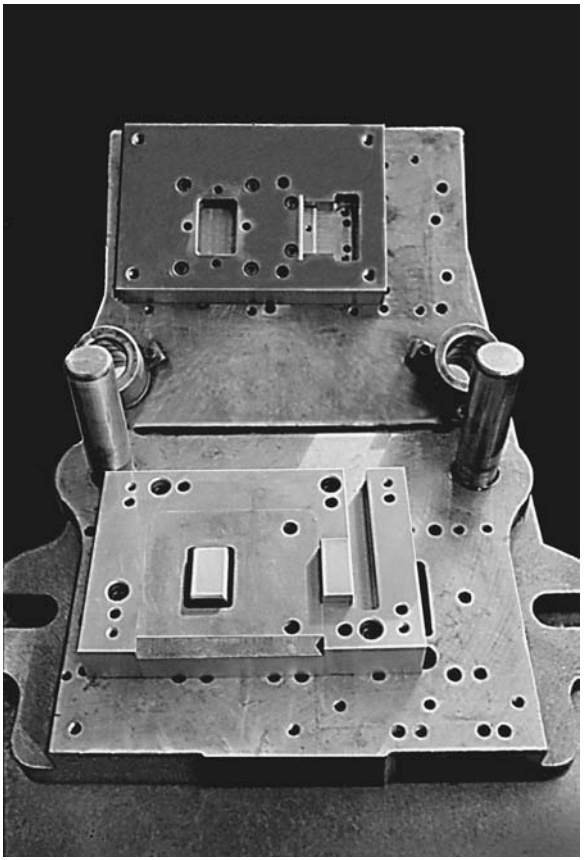

FIGURE 1-48 Forming die for part from Fig. 1-46. (*Reprinted with permission from Roselle Tool and Die, Roselle Park, NJ.*)

Serious students of die design should never neglect the importance of actual observation of dies running in production. They should be out there, in the shop, whenever possible and watch the tooling in operation or when being repaired or sharpened, observe the strip, check the progression sequence, evaluate the direction of punching, and scrutinize the toolmakers as they put the dies together.

Theory is great and highly relevant. But without practical experience it may often prove inadequate.

1-4 ELIMINATION OF SECONDARY OPERATIONS THROUGH BETTER PART DESIGN

Secondary operations are always undesirable. They can be slow and laborious and tie up the factory floor for days. They can also be tedious and damage-prone. But above all, they can drive the cost of production to unplanned heights. Therefore, secondary operations should be avoided whenever possible.

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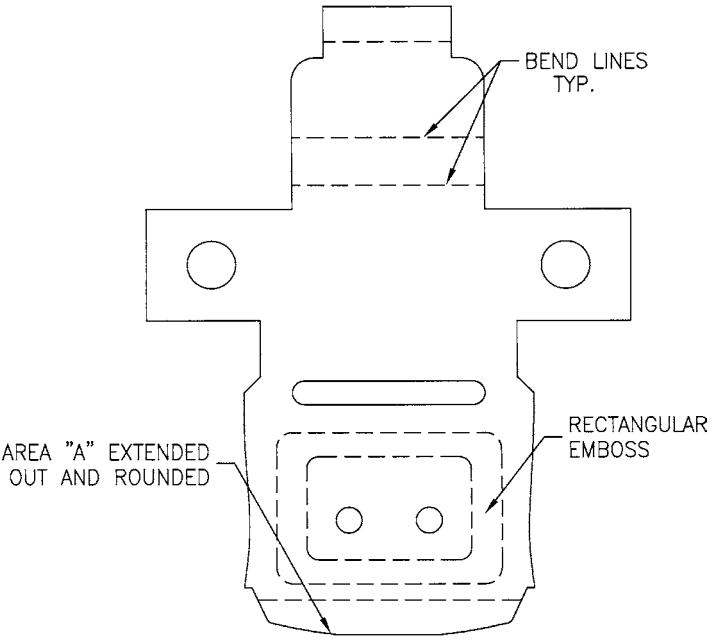

FIGURE 1-49 Flat layout of the part. (*Reprinted with permission from Englert Inc., Perth Amboy, NJ. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

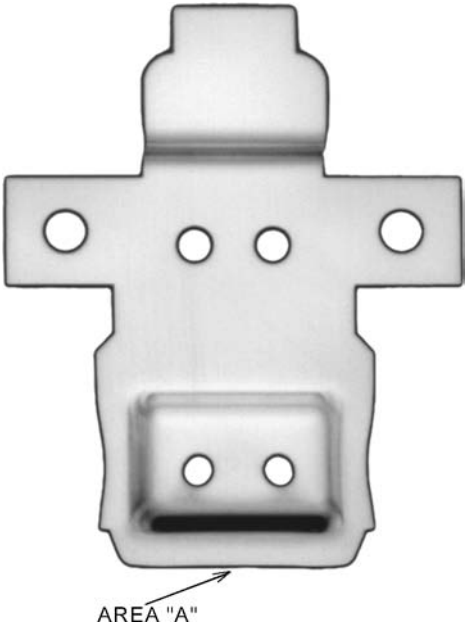

FIGURE 1-50 Straight flange. (*Reprinted with permission from Englert Inc., Perth Amboy, NJ. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

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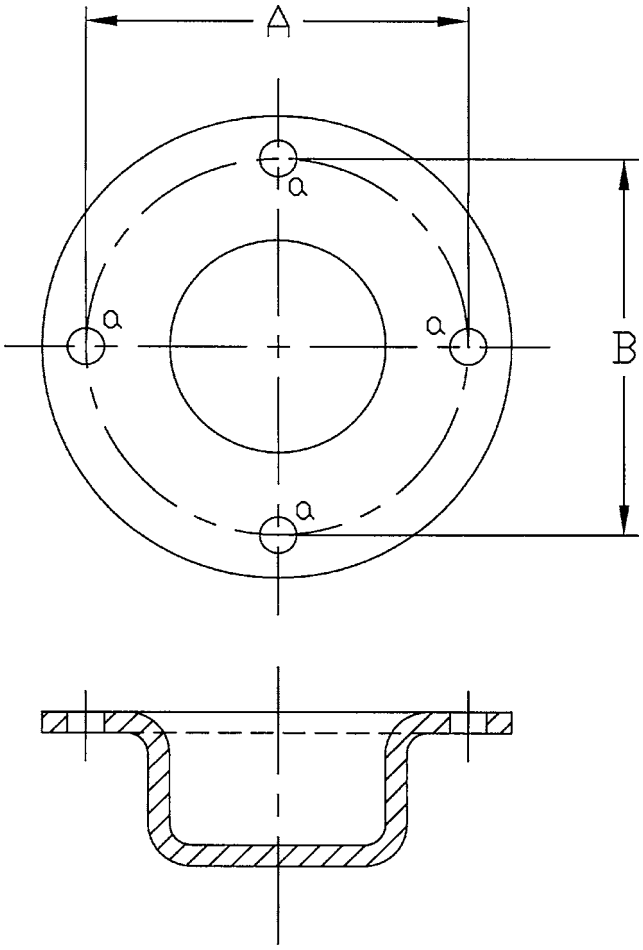

FIGURE 1-51 Control of dimensions in drawn parts.

The first place to look for their elimination is the design of the part. Often a problematic operation may not actually be needed, or perhaps can be replaced by a much less troublesome process.

Tighter than customary tolerances are sure indicators of a problem within the part's design or function. There the designers are trying to protect themselves so that in the case of emergency they can point an accusing finger at the shop, which did not hold a particular dimension that often would be impossible to hold at all.

The products' application and function should be scrutinized when looking for the operations worth eliminating. Yet, in die design, the most obvious problems to address are elimination or replacement of welded-on segments and other costly and work-intensive additions.

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BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

1-4-1 Welding of Added-On Segments as Replaced by Bent-Up Portions of the Original Part

Welding is a very expensive process, where every inch-long portion of a seam may cost more than the whole part produced by a die. Welding also gives a rise to high stresses in the welded part and it may cause distortions and breakages. Often a nondetected flaw may be the reason for a failure of the weld. Additionally, aluminum is quite difficult to weld at all.

For these reasons, if welding can be replaced by some other method of joining, then that method should be used by all means. But, which methods are available to choose from?

True, parts can be joined with adhesives or rivets, or screws and nuts, and other means. However, these methods cannot be applied in all circumstances and certainly only a few of them can be compared to the sturdiness of the properly welded section.

Obviously, when possible, welding should best be replaced by such a design change that allows for its complete elimination and yet it provides the part with the same service as a welded-on feature. Some ideas appear in Fig. 1-52.

Here, the groove in each block is to be located at a certain distance off the sheet-metal wall. Attaching the grooved blocks with screws will not provide them with the needed dimensional accuracy, since every screw-mounting opening requires quite a clearance for the screw to fit. In this case, perhaps welding the blocks on may prove to be a more appropriate method of attachment.

We may sum up the facts of importance presented here as follows:

- Groove in the two blocks
- Height of the groove off the block's surface
- Four mounting openings in the block
- Height of the block

If we sketch these areas on a piece of paper and evaluate how can they be made of sheet metal, it only remains to fill in the spaces and the replacement part is found. No assembly work to be done, no additional hardware to be used, and no costly steel blocks. The part is simple and light, and if made from the proper grade of steel it will surely be sturdy enough to replace the complicated assembly on the left.

Where necessary, stiffeners can be added in the die by denting the bend across, as shown. These indentations will secure the two prongs with grooves in their proper location by making the bend more rigid and unyielding.

Shown in Fig. 1-53 are three brackets attached to the basic sheet-metal part by spot welding. The spot-welding operation is costly; it may drive the scrap rate much higher than anticipated and it may require some elaborate fixturing, since the two openings (indicated as bearing surfaces) must line up.

Further, there are four parts to this assembly, all die or piecemeal products, all costly to make. Again, the portions most important for the proper evaluation are:

- Two bearing holes
- Their height off the bottom of the bracket
- Two sets of mounting holes on each side flange
- Bottom bracket with additional three openings

If we place these in correct proportions on a piece of paper, we may immediately realize that all these points of interest have enough sheet-metal space in between to form these brackets with no harm done to the main part. Not only will such a redesigned part be

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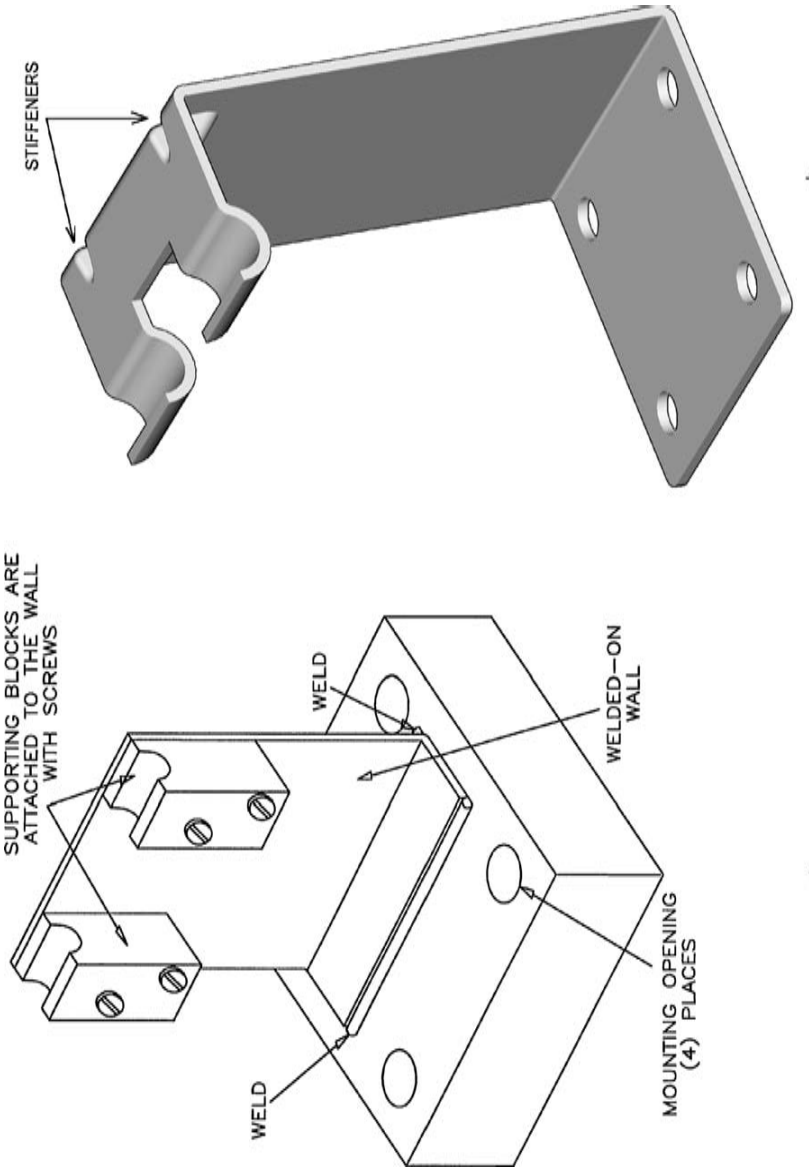

FIGURE 1-52 Welded assembly and its sheet-metal replacement.

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BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

cheaper to produce, but the location and accuracy of the two bearing surfaces will be much more controllable and precise.

If we scrutinize the part further, we may begin to question the necessity of three mounting holes on each side flange. A single screw (per side) can carry quite a load, provided the part is positioned over a movement-restricting arrangement in the other two openings. It also takes much more time to assemble six screws with washers and nuts than two. If the part were to be used for equipment produced a few pieces at a time, the mounting holes would better be left alone. But if these products run into hundreds or thousands, a change in design would be more than justified.

The best way to replace a group of assembly screws is to create posts on the adjoining members of the assembly, slide the bracket over them (using perhaps an alternative type of openings, shown in detail "P" of Fig. 1-53), and secure in place with only one screw per side. The posts may be bent-up sections of sheet metal of the connecting part formed to resemble hooks—they surely will carry the load quite nicely. Screws would be there mainly for security against shifting or other displacement.

1-4-2 Use of Sheet-Metal Hardware in Replacement of Drilled and Tapped Holes, Offsets, Bosses, and the Like

Sheet-metal hardware is quite commonly used in replacement of previously drawn and threaded bosses or in lieu of additional blocks, which often had to be attached by quite labor-intensive means or as a replacement of various brackets, supports, or standoffs.

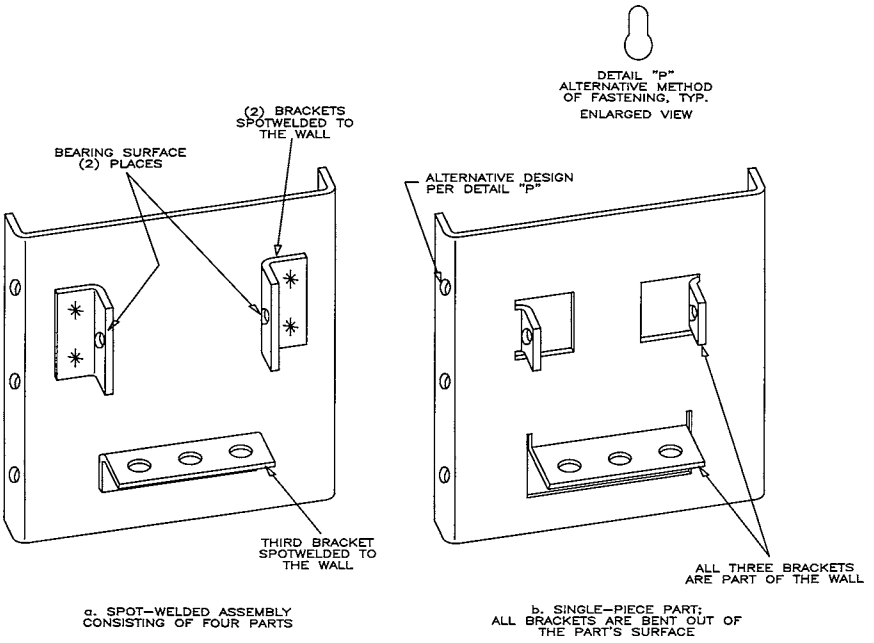

FIGURE 1-53 Spot-welded assembly, as replaced by a single sheet-metal part.

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For heavier work, welded nuts, screws, and pins can be utilized. They will suffice for materials of 0.025 to 0.187 in. [0.65 to 4.50 mm] sheet thickness, and where spot welding is not objectionable for the design or function requirements.

In welded nuts, threaded inserts, or pins, there are tree projections located on the surface which is to be attached to the connecting sheet-metal part (Figs. 1-54, 1-55). These are to assure the contact and easy fusing of hardware to the sheet-metal part. The method of assembly is either spot welding or projection welding.

For lighter-gauge applications, up to 0.090 in. [2.25 mm] sheet thickness, clinching fasteners will prove quite useful. They come in a wide range of designs and applications:

- Self-clinching fasteners, easily squeeze-installed into a punched or drilled hole, where they lock themselves in place, flush with the opposite side of the sheet.
- Floating fasteners allow for ±0.015 in. [0.38 mm] mating hole misalignment.
- Blind and threaded-standoffs are commonly used for printed circuits applications.
- Self-clinching studs (Fig. 1-56), nuts (Fig. 1-57), and standoffs with a snap-top adjustment are a continuation of a wide assortment of this type of hardware.

1-4-3 Die-Produced Parts to Replace Other Products, Such as Castings, Forgings, or Plastics

Many die-stamped parts are used to replace castings, forgings, and parts made by various other method because die production is faster, more precise, and consistent. Dimensions are easily controlled and often no subsequent grinding, drilling, metal removal, and other extensive finishing is required.

Lately, however, the trend is to replace some sheet-metal parts with plastics often to the disadvantage of the buyer. Everything has its time and place, and plastic materials even though displaying many admirable properties, sometimes just do not suffice. Sheet metal is definitely more sturdy and yet flexible, the effect of its aging is more negligible, and the weathering effect has no influence on it if properly coated.

FIGURE 1-54 Threaded stud with projections for welding. (*Reprinted with permission from The Ohio Nut and Bolt Co., Berea, OH.*)

FIGURE 1-55 Flanged weld nut. (*Reprinted with permission from The Ohio Nut and Bolt Co., Berea, OH.*)

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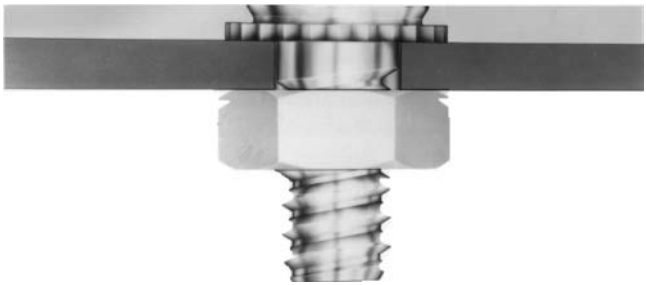

FIGURE 1-56 Concealed head, self-clinching threaded stud. (*Reprinted with permission from PEM Fastening Systems, a PennEngineering Company, Danboro, PA.*)

Plastics are less sturdy, they change colors with time, they suffer from weathering effects, and the aging process may cause their total disintegration. If they are soft and yielding, their life cycle is often threatened. If they are hard and inflexible, they break. In some cases where plastic parts replaced products previously made of metal, a wire frame or other metal framework had to be used for support. Extensive ribbing and wall support is common with plastics as well, and it makes the products harder to service and maintain.

Plastic parts used in high-heat areas such as car front panels often disintegrate with time, and literally "dust away." A threaded plastic part takes the screw only once, the first time. With every additional removal and insertion the functionality of thread diminishes.

It is obvious that there are many opportunities for the eager die designer who is willing to devote his or her time and brain capacities to the task of innovating the already innovated. The sky is the limit.

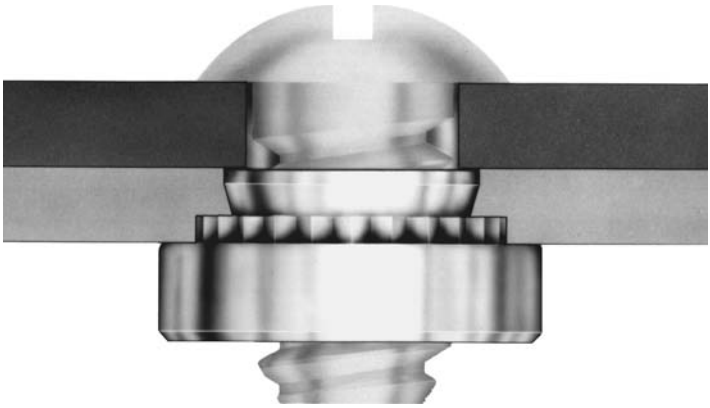

FIGURE 1-57 Self-clinching nut. (*Reprinted with permission from PEM Fastening Systems, a PennEngineering Company, Danboro, PA.*)

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1-5 ADVANTAGES OF SHEET-METAL APPLICATION

A definite advantage of sheet-metal parts is the uniform thickness of the material, which can be controlled up to a close range with tolerances. Industry standards on flat sheets are as shown in Table 1-6. Anything tighter is more costly.

Tolerances for die-punched holes can be considered quite impressive. Some basic numbers are given in Table 1-7. Perhaps it should be pointed out that the tightest linear tolerance range of today's automatic punch presses is ±0.003 in. [0.075 mm] for shorter distances—hole-to-hole only.

Sheet-metal parts are often of utmost importance as covers and liners in electrical products, where they provide for *radio-frequency* (RF) shielding as well. With covers made of plastics, the particles of RF shielding material can be added to the plastic melt or later spray-applied to the inner surfaces of finished products. However, this can become impractical or too costly.

The magnetic or non-magnetic properties are additional factors to be considered in sheet-metal design and use. The material's resistance to heat and fire along with its capability of heat dissipation are exceeded only by ceramics.

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BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

TABLE 1-6 Thickness Tolerances of Strip Stock

All values are in inches. Thickness tolerance plus or minus. Tolerance is measured across the width, but not less than $^3/_8$ in. off the edge.

Aluminum sheet				
Stock thickness, in.	Width, in.			
	Up to 18	18–36	36–48	48–54
0.011–0.017	0.0015	0.0015	0.0025	0.0035
0.018–0.028	0.0015	0.002	0.0025	0.0035
0.029–0.036	0.002	0.002	0.0025	0.004
0.037–0.045	0.002	0.0025	0.003	0.004
0.046–0.068	0.0025	0.003	0.004	0.005
0.069–0.076	0.003	0.003	0.004	0.005
0.077–0.096	0.0035	0.0035	0.004	0.005
0.097–0.108	0.004	0.004	0.005	0.005
0.109–0.140	0.0045	0.0045	0.005	0.005
0.141–0.172	0.006	0.006	0.008	0.008
0.173–0.203	0.007	0.007	0.010	0.010
0.204–0.249	0.009	0.009	0.011	0.011
Carbon steel, Cold rolled				
Stock thickness, in.	Width, in.			
	Up to 3	3–6	6–9	9–12
0.011–0.017	0.00075	0.00075	0.001	0.001
0.020–0.023	0.001	0.001	0.0015	0.0015
0.023–0.026	0.001	0.0015	0.0015	0.0015
0.026–0.032	0.0015	0.0015	0.002	0.002
0.032–0.035	0.0015	0.002	0.002	0.002
0.035–0.040	0.002	0.002	0.002	0.002
0.040–0.069	0.002	0.0025	0.0025	0.0025
0.069–0.100	0.002	0.0025	0.003	0.003
0.100–0.161	0.002	0.003	0.003	0.003
0.161–0.200	0.0035	0.004	0.004	0.0045
0.200–0.250	0.004	0.0045	0.0045	0.005
Carbon steel, Hot rolled				
Stock thickness, in.	Width, in.			
	Up to 3	3–6	6–9	12–15
0.025–0.034	0.003			
0.034–0.044	0.003	0.003		
0.044–0.056	0.003	0.003	0.004	0.005
0.056–0.097	0.004	0.005	0.005	0.006
0.098–0.118	0.004	0.005	0.005	0.007
0.118–0.187	0.005	0.005	0.005	0.007
0.187–0.203	0.006	0.006	0.006	0.007
0.203–0.230			0.006	0.007

(*Continued*)

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TABLE 1-6 Thickness Tolerances of Strip Stock (*Continued*)

All values are in inches. Thickness tolerance plus or minus. Tolerance is measured across the width, but not less than $^3/_8$ in. off the edge.

Stainless steel				
Stock thickness, in.	Width, in.			
	Up to 3	3–6	6–9	9–12
0.011–0.012	0.001	0.001	0.001	0.001
0.012–0.013	0.001	0.001	0.001	0.0015
0.013–0.019	0.001	0.001	0.0015	0.0015
0.020–0.025	0.001	0.0015	0.0015	0.0015
0.026–0.029	0.0015	0.0015	0.0015	0.0015
0.029–0.034	0.0015	0.002	0.002	0.002
0.035–0.040	0.002	0.002	0.002	0.002
0.041–0.049	0.002	0.0025	0.003	0.003
0.050–0.099	0.002	0.003	0.003	0.003
0.100–0.160	0.002	0.003	0.004	0.004
0.161–0.187	0.003	0.004	0.004	0.004

All values are in millimeters. Thickness tolerance plus or minus. Tolerance is measured across the width, but not less than 10 mm off the edge.

Aluminum sheet				
Stock thickness, mm	Width, mm			
	Up to 500	500–1000	1000–1250	1250–1500
0.28–0.43	0.038	0.038	0.063	0.089
0.46–0.71	0.038	0.050	0.063	0.089
0.74–0.91	0.050	0.050	0.063	0.10
0.94–1.14	0.050	0.063	0.076	0.10
1.17–1.73	0.063	0.076	0.10	0.13
1.75–1.93	0.076	0.076	0.10	0.13
1.96–2.44	0.089	0.089	0.10	0.13
2.46–2.74	0.10	0.10	0.13	0.13
2.77–3.56	0.11	0.11	0.13	0.13
3.58–4.37	0.15	0.15	0.20	0.20
4.39–5.16	0.18	0.18	0.254	0.254
5.18–6.32	0.23	0.23	0.28	0.28
Carbon steel, Cold rolled				
Stock thickness, mm	Width, mm			
	Up to 75	75–150	150–225	225–300
0.28–0.43	0.019	0.019	0.025	0.025
0.51–0.58	0.025	0.025	0.038	0.038
0.58–0.66	0.025	0.038	0.038	0.038
0.66–0.81	0.038	0.038	0.050	0.050
0.81–0.89	0.038	0.050	0.050	0.050
0.89–1.02	0.050	0.050	0.050	0.050

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BASIC DIE DESIGN AND DIE-WORK INFLUENCING FACTORS

TABLE 1-6 Thickness Tolerances of Strip Stock (*Continued*)

All values are in millimeters. Thickness tolerance plus or minus. Tolerance is measured across the width, but not less than 10 mm off the edge.

Carbon steel, Cold rolled				
Stock thickness, mm	Width, mm			
	Up to 75	75–150	150–225	225–300
1.02–1.75	0.050	0.063	0.063	0.063
1.75–2.54	0.050	0.063	0.076	0.076
2.54–4.09	0.050	0.076	0.076	0.076
4.09–5.08	0.089	0.10	0.10	0.114
5.08–6.35	0.10	0.114	0.114	0.13
Carbon steel, Hot rolled				
Stock thickness, mm	Width, mm			
	Up to 75	75–150	150–225	225–385
0.64–0.86	0.76			
0.86–1.12	0.76	0.76		
1.12–1.42	0.76	0.76	0.10	0.13
1.42–2.46	0.10	0.13	0.13	0.15
2.49–3.00	0.10	0.13	0.13	0.18
3.00–4.75	0.13	0.13	0.13	0.18
4.75–5.16	0.15	0.15	0.15	0.18
5.16–5.84			0.15	0.18
Stainless steel				
Stock thickness, mm	Width, mm			
	Up to 75	75–150	150–225	225–300
0.28–0.30	0.025	0.025	0.025	0.025
0.30–0.33	0.025	0.025	0.025	0.038
0.33–0.48	0.025	0.025	0.038	0.038
0.51–0.64	0.025	0.038	0.038	0.038
0.66–0.74	0.038	0.038	0.038	0.038
0.74–0.86	0.038	0.050	0.050	0.050
0.89–1.02	0.050	0.050	0.050	0.050
1.04–1.24	0.050	0.063	0.076	0.076
1.27–2.51	0.050	0.076	0.076	0.076
2.54–4.06	0.050	0.076	0.10	0.10
4.09–4.75	0.076	0.10	0.10	0.10

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TABLE 1-7 Hole Size Tolerances

Dimensions in inches

Hole diameter, in.	Material thickness, in.				
	0.020–0.040	0.041–0.070	0.071–0.093	0.094–0.156	0.157–0.250
0.125	0.002	0.005	0.008	0.010	
0.141	0.003	0.006	0.008	0.010	
0.250	0.004	0.008	0.010	0.011	0.020
0.437	0.006	0.008	0.010	0.011	0.020
0.687	0.009	0.010	0.010	0.011	0.020

Dimensions in millimeters

Hole diameter, mm	Material thickness, mm				
	0.50–1.00	1.05–1.75	1.80–2.35	2.40–3.95	4.00–6.35
3.00	0.05	0.13	0.20	0.25	
3.50	0.75	0.15	0.20	0.25	
6.50	0.10	0.20	0.25	0.28	0.50
11.00	0.15	0.20	0.25	0.28	0.50
17.00	0.23	0.25	0.25	0.28	0.50

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CHAPTER 2
THE THEORY OF SHEET METAL BEHAVIOR

2-1 SHEET METAL AND ITS BEHAVIOR IN METAL STAMPING PROCESS

The metal stamping process can alter the sheet-metal material in many ways. Parts may be blanked, pierced, drawn, formed, or embossed, just to name a few basic operations. Each of these processes exerts its influence upon the structure of the material: that of the part and that of the scrap.

Often, a congested piercing can cause stresses that will produce an increase in area measurements of that particular section, which is called *bulging*, or *oilcan effect* (from oilcan's snapping back and forth). Forming or drawing, on the other hand, can produce wrinkling, tearing, ironing, or undesirable folding of metal.

2-2 PLASTICITY THEORIES

During the forming or deforming process, any metal material, with all its mechanical, electrical, and other properties, will go through a transformation from its elastic state to plastic. These changes are forced upon its structure by various stresses, temperature changes, and speed of the forming application, among others. The changes may occur either along the plane of the highest concentration of potential energy, or along the plane of maximum shear stress.

Naturally, such an array of influences cannot fail to produce considerable changes in the part's structure and appearance. Some changes may have been originally planned for, and for that reason these can be considered beneficial. Unfortunately, there can be changes that are detrimental to the outcome of the performed operation and these result in a defected product.

In an attempt to control the material-related defects in sheet-metal forming, several theories pertaining to its plasticity were developed. Plasticity of metal is the capacity to withstand the application of force, which, when excessive, may produce its deformation. When this force is small enough to fit within the material's *yield strength* limit, the deformation is only temporary, and after the release of the pressure, the material returns to its initial state. However, when the force exceeds the yield strength of that particular material, the resulting deformation of its crystal lattice remains permanent and the part is permanently deformed, or perhaps, formed.

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Stress force applied to the material can be categorized to fit into one of the three following groups:

- *Linear application of stress*, with the stress applied along a single axis only, leaving the other two axes stress-free.
- *Plane-type application of stress*, with stresses applied along any two axes, while the third axis remains stress-free.
- *Volummetric application of stress*, where stresses act along all three axes.

Needless to say, the vast majority of metal-forming processes belong to the third, volummetric group.

Plasticity theory is a mathematically oriented approach to evaluation of metal-structure altering (forming) processes. However, its mathematical equations, when used to solve actual problems, were often found quite inadequate and sometimes outright invalid. For that reason, a method called an *elementary plasticity theory* was developed.

According to the elementary plasticity theory, various forces can be calculated without immediately considering the metallurgical properties of the material. The behavior of these forces can thus be evaluated and their influence during metal's shape-altering process predicted. This theory, based on actual records of macroscopic observations of the deformation stage, deals with concrete data pertaining to particular qualities of the material in question, such as the stress/strain rate and yield criteria in tension and compression. A material's background data, such as metallurgical processes chosen for its manufacture are mostly omitted.

During the metal-forming (or deforming) process, a displacement of metal material occurs, and its direction coincides with the direction of forces acting upon it. If we take a small particle of material and make it a representative of the whole mass, the displacement looks similar to that shown in Fig. 2-1.

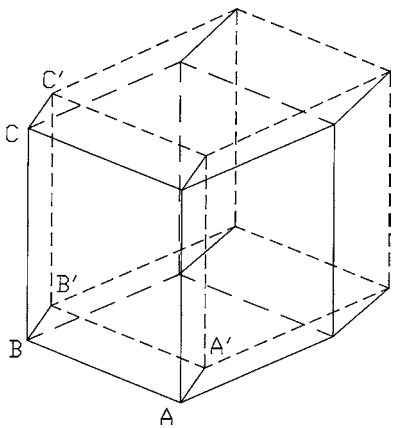

FIGURE 2-1 Displacement of a particle in time Δt.

The amount of time such a displacement needs to occur is denoted by Δt. During that period, points *A, B, C* will change their location to *A′, B′,* and *C′*, in congruence with the direction of forces acting upon them, and this movement will permanently alter the shape of that particle. We may generalize that if at least two points within any material change their relative location during the time interval Δt, that particle is exposed to the influences of deformation, or strain.

The type of deformation most often considered in metal-forming processes is permanent deformation. The nonpermanent deformation, also called elasticity, is usually neglected, unless it falls into the category called *springback,* which shall be discussed later.

There are two definitions of the material's condition, applicable to the process of deformation: *homogeneous* and *anisotropic.* A material is homogeneous when each of its particles has the same properties. The properties of an anisotropic material differ with the coordinate system. For example, wood may be a homogeneous material, since its characteristics are constant throughout its entire volume. But when in deformation, its reaction to the force applied *along* its fibers is different from its reaction to the force coming *across* them. For this reason, wood is an anisotropic, yet a homogeneous material.

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THE THEORY OF SHEET METAL BEHAVIOR

Metal, prior to forming, is usually homogeneous and isotropic. But after being permanently deformed, it may become *anisotropic*, and if an uneven deformation has been achieved, it would become inhomogeneous as well.

Anisotropy is the opposite of isotropy. An *isotropic* polycrystalline metallic material is one whose properties are the same in all directions. In forming and drawing operations, anisotropy affects the material flow. Even the deep drawing limits are based on the effects of anisotropy.

Forming capacities of all metal materials are known to be temperature dependent: With higher temperatures the forming limit of metal is expanded. This is mainly due to the recrystallization processes within the matter, which are temperature dependent as well, and which allow for considerably more elastic behavior when warmed up.

Note: Recrystallizing temperatures below 200°C or ~400°F are to be held for an hour in order to alter the material's lattice without altering its strength at the same time.

If we cut a body, upon which various stresses are acting, in half, we shall disrupt the forces holding that body together. We then add a resultant to these stresses and attach it to the plane of the cut to balance their influence. According to the direction of this resultant, we recognize normal stress δ (compressive or tensile) and tangential stress τ.

Several theories describe the flow of material during various forming processes. All these approaches may be grouped within two basic categories:

1. Analytical methods, consisting of:
   - Strip or slab theory
   - Slip-line theory
   - Bound theorems
   - Theory of weighted residuals
2. Experimental-analytical methods, such as:
   - Axisymmetric forming processes
   - Methods utilizing the visibility of plastic flow
   - Hardness method
   - Macroscopic methods
   - Finite element analysis

2-2-1 Strip or Slab Theory, or the Equilibrium Method

Strip or slab theory (see Fig. 2-2*a*) is used for evaluation of processes that fall into the plane deformation group, such as rolling. This method isolates a representative volumnar element in the material, *dx*, and on the basis of its behavior, it assumes that:

- The velocity of material v_x, is constant at every point of a cross section of the flow (see Fig. 2-2*a*).
- The volume of material is constant as well.
- Friction between the material and the tooling exists. Such friction is constant, and the tooling is symmetrical.
- The rate of change in height of the strip h_R depends on the slope of the tool in point of contact, on the velocity v_T at which the opposite boundaries approach each other, and on the velocity of the strip v_x.
- The weight and inertia forces are negligible.

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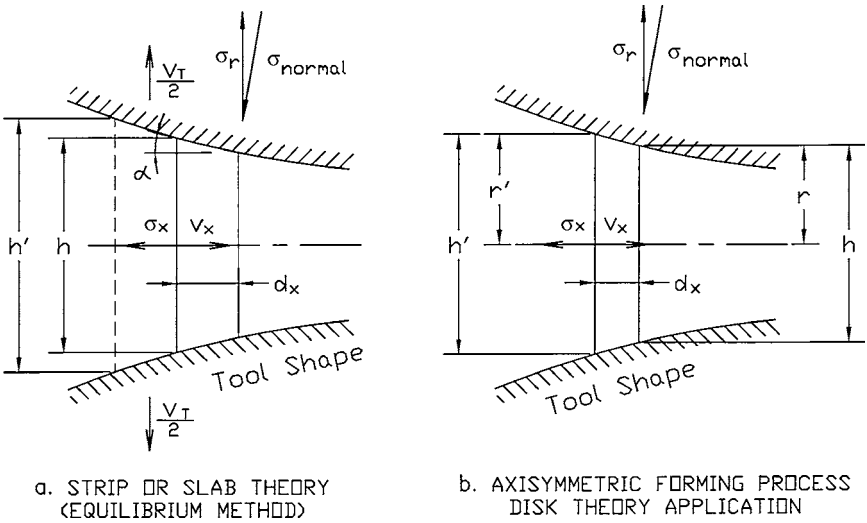

FIGURE 2-2 Plasticity theories.

A formula, which calculates the rate of change in height of a moving tool, is:

$$h_R = \frac{\delta h}{\delta t} + v_T = \frac{\delta h}{\delta x} v_X + v_T \tag{2-1}$$

where h_R is the rate of change between h and h'. This formula when applied to a stationary tool becomes:

$$h_R = \frac{\delta h}{\delta t} = \frac{\delta h}{\delta x} v_x \tag{2-2}$$

This type of motion in metal results in a homogeneous matter after forming. The natural strain along y axis φ_y can be calculated as follows:

$$\varphi_y = \ln \frac{h'}{h} \tag{2-3}$$

and the strain rate φ_R becomes:

$$\varphi_R = \frac{\delta \varphi_y}{\delta t} = \frac{h_R}{h} \tag{2-4}$$

2-2-2 Slip-Line Theory

Prior to the development of three-dimensional models, this theory was used for assessment of plane deformation, since it indicates the direction of the maximum shear stress and the maximum shear strain rate. These values are used for a numerical evaluation of stress distribution throughout the deformed portion and its boundaries, upon which the loads exerted

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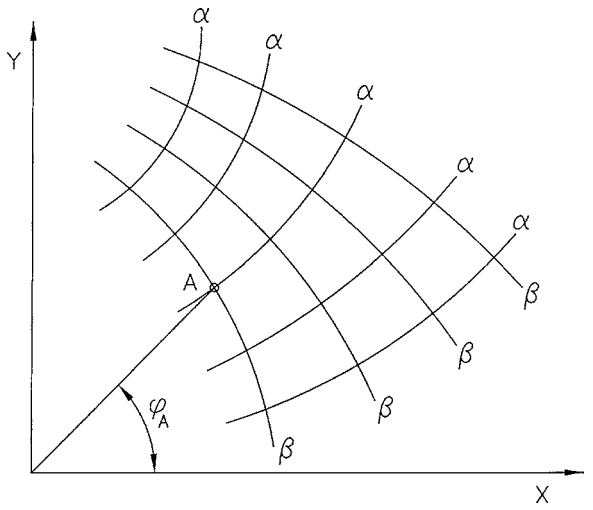

FIGURE 2-3 Network of Lüders' lines, or slip-lines.

by tools are acting. Later, this theory was extended to some cases of axial symmetry, even though it could not be reasonably applied to the majority of axisymmetric problems. The name of this theory is derived from the physical observation of plastic, the flow of which seems to be a result of microscopic slip on an atomic scale along its crystallographic plane.

The application of this method consists of constructing a network of lines, also called *Lüders' lines* (shown in Fig. 2-3). These lines, when applied to the surface of the part are used for evaluation of those forming processes during which there is an absence of strain hardening. The technique of assessment is not time dependent and the forming pressure is considered static and isothermic.

It is given that the slip lines α and β are orthogonal, and that they cut through main vectors of tension under an angle $\pi/4$. Differential equations of these two types of lines will come out as tangents:

$$\alpha\text{-}calculation: \quad \frac{dy}{dx} = \tan\varphi \tag{2-5}$$

$$\beta\text{-}calculation: \quad \frac{dy}{dx} = \tan\left(\varphi + \frac{\pi}{2}\right) = -\cot\varphi \tag{2-6}$$

2-2-3 Bound Theorems

This method of evaluation divides the surface into triangular segments (see Fig. 2-4) sliding across each other. Inside these segments is a homogeneous velocity field with constant velocity values at any point within the given area. It is speculated that the rate of work done by such surficial segments is:

- With *lower bound theorem* greater than or equal to the rate of work performed by any other segments that can satisfy the same equilibrium conditions and stress boundary descriptions. A sum of instantaneous outputs of inner forces is considered equal to the

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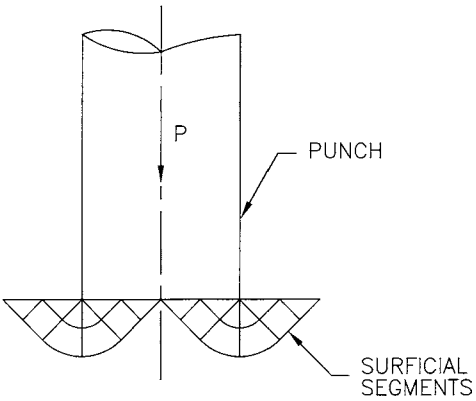

FIGURE 2-4 Bound theorem's representation.

forming pressure needed to alter the material. However, it is not always easy to locate statistically similar stress areas, for which reason upper bound theorem is often preferred as a means of evaluation.

- With *upper bound theorem* the rate of work done by surficial segments is smaller than or equal to the rate of work attributable to any other segments, displaying the same velocity arrangements, whose material content can be considered incompressible. Calculation of such output will provide an approximate assessment of the forming force, on the basis of which tooling and machinery may be chosen.

2-2-4 Theory of Weighted Residuals

This method can be applied to simple deformation processes, where it was found proficient at delivering acceptable results through approximation of stress and strain cases of complex problems. It is based on the law of energy conservation with the volume of flowing material considered constant, and equilibrium conditions satisfied. Each stress is represented by a series of functions such as polynomial expressions outfitted with arbitrary parameters.

It maintains that for small virtual movements (δ_u, δ_v, δ_w), the work of all inner and outer forces is minimal, which is attributable to its equilibrium condition. Therefore, the equation applies:

$$\delta W_{\text{in}} - \delta W_{\text{out}} - \delta W_F = 0 \tag{2-7}$$

Considering the constancy of volume and ignoring elastic changes within the material, the formula may be rewritten as:

$$W_{\text{in}} - W_{\text{out}} - W_F = 0 \tag{2-8}$$

This equation actually claims that the work of inner forces (W_{in}), used up for plastic deformation of the material, is in equilibrium with the work of outer active forces (W_{out}), combined with the value of surficial friction (W_F).

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2-2-5 Axisymmetric Forming Processes, or Disk (Tube) Theory

This theory assumes that:

- Tooling has no velocity, the only velocity being that of v_x.
- The material flow is symmetric along one axis.

The natural strain φ can be calculated by using the formula:

$$\varphi = 2 \ln \frac{r'}{r} \tag{2-9}$$

and the strain rate φ_R becomes:

$$\varphi_R = 2\frac{r_R}{r} = -\frac{\delta v_x}{\delta x} \tag{2-10}$$

Stresses along the material flow δ_f (see Fig. 2-2*b*) will be:

$$\pm \delta_f = \delta_x - \delta_r \tag{2-11}$$

2-2-6 Methods Utilizing the Visibility of Plastic Flow

Since the exact mathematical representation of changes within the formed part is practically impossible, allowing for visibility of changes using the elementary surface representation may be utilized instead. There are three methods of such depiction.

2-2-6-1 Visioplasticity. Visioplasticity is based on an assessment of vectors of velocity. For this purpose it utilizes a grid structure assigned to the surface of material often by photographic means. This pattern, showing a distortion in areas of deformation, creates a dependency of directional tensors of tension and those of deformation.

The velocity of the flow can be figured out from the distances that the points under deformation have moved. These velocities are considered constant, and stresses are represented by grid lines, not by arbitrary points. The equilibrium is no longer applicable with this method.

Such a technique cannot be used to predict further behavior of the material, but it is valued for the detailed analysis of the distribution of stresses, strain, and strain rate in any portion of the deformed area.

2-2-6-2 Photoelasticity. Photoelasticity uses models made of linear elastic materials, such as organic glass, which are exposed to outside influences within their elastic areas only. In comparison to this method, photoplasticity uses models made of linear-plastic materials.

Both these methods are based on the principle of *optical refraction*, where the force-affected areas display a difference in light intensity. Dark areas contain similarly oriented tension, while colored stripes depict differences between tension and deformation.

2-2-6-3 Moiré Method. This method is based on the principle of geometric interferences. A network applied to the product's surface changes its linear arrangement under deformation. By attaching a reference network of the same lines, unaltered by any outside

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influences, a comparison of the two patterns is possible. Dark and light abnormalities or moiré stripes may be observed where changes of the material structure occur.

2-2-7 Hardness Method

As a method of assessment, the hardness comparison method considers a dependency between the hardness of deformed material and that, which is unaltered in any way. By the distribution of hardness variation the area of deformation and the amount of tension within the material may be established.

2-2-8 Macroscopic Methods

Macroscopic methods allow for observation of material changes, which are represented by changes in patterns originally assigned to the surface of the parts. The network of lines may be printed upon the part or attached by any other means. Sample patterns are shown in Fig. 2-5.

2-2-9 Miscellaneous Theories

During the process of development and refinement of plasticity theories, various researches added their opinions in the form of calculations or specifications. The slip-line theory is actually based on the research of Hencky and Prandtl, with von Misses adding his flow rule to it. Geiringer supplied the equations for the velocity assessment. The weighted residuals method gained through the work of Lagrange, while Thompson established the dependency of the speed of change and tension of material in visioplasticity. A considerable input was supplied in the form of Prandtl-Reuss and von Misses research.

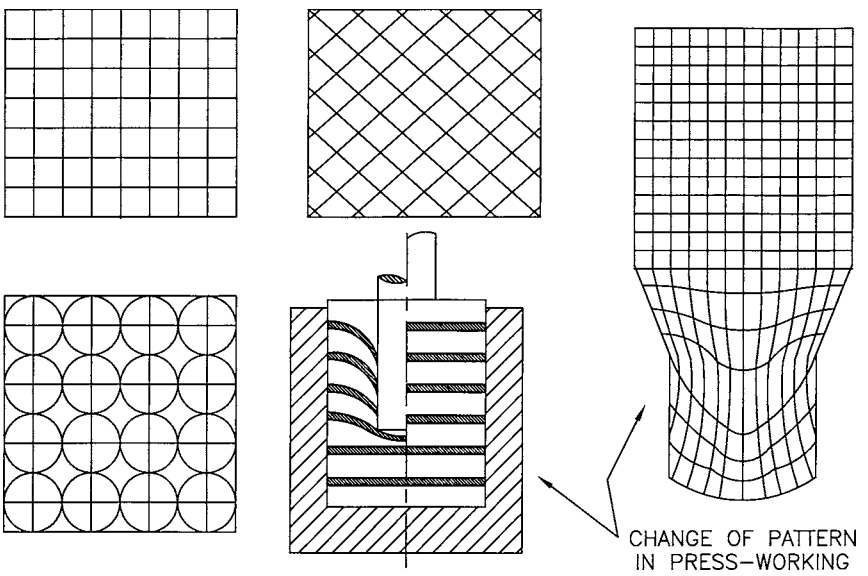

FIGURE 2-5 Sample patterns used with macroscopic method of evaluation.

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2-2-9-1 Prandtl-Reuss Plasticity Theory. This theory assumes that with the application of force on a material, elastic strain prevails until yield-strength has been arrived at. From there, the force does not have to be increased any further for the permanent deformation to occur (an elastic, perfectly plastic material).

2-2-9-2 Von Misses Plasticity Theory. This theory is based on a simplified assumption that the material is under no strain until the yield-strength has been attained. The material therefore behaves like a rigid body (a rigid, perfectly plastic material). This theory is not so erroneous as it may seem at the first glance, for permanent strains are much greater than their smaller and consequently negligible elastic counterparts.

However, the exact solution of the plasticity of material is not easily obtainable because of the great complexity of the problem. Therefore, only simple results must be sought, with complex problems simplified and approximated.

2-2-10 Finite Element Analysis (FEA)

Lately, this is the most often used method for its complex calculations, which can now be so readily solved by computers. The material in question is divided into minute particles joined at their corners. The stress throughout each particle is considered uniform, and the distortion is computed by using any conventional mathematical theory. The final behavior of the material is obtained through evaluation of the influences these particles exert on each other.

Naturally, since all actual processes within the material are very complex, their mathematical and graphical representation is simplified. Even elements constituting the representation of the part's construction are but simple geometrical shapes. For example, an analysis of axisymmetric tension uses triangular or rectangular cross-sectional cuts as shown in Fig. 2-6.

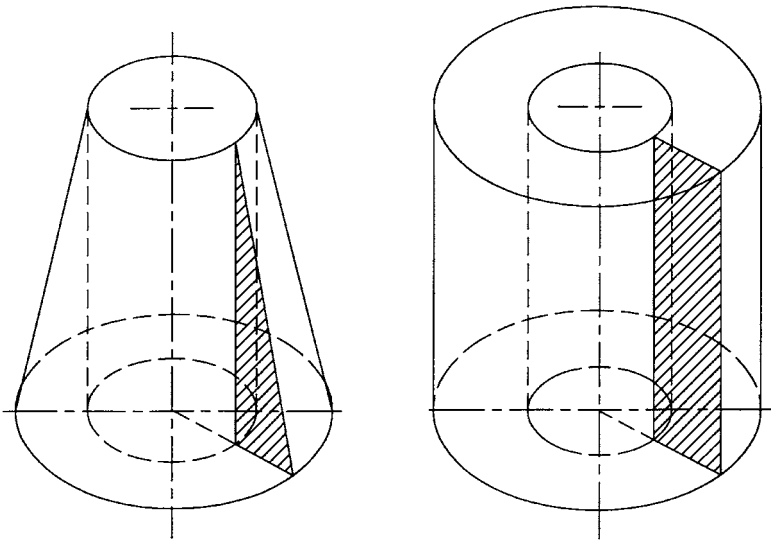

FIGURE 2-6 Axisymmetric geometric shapes used in finite element analysis.

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Computerized finite element analysis is today obtainable as either complement software to many 3D *computer aided design* (CAD) packages, or as a standalone program. The software can solve in minutes what engineers of yesterday would have calculated for weeks. Problems of buckling, deformation, static stresses, thermal analysis, and similar tasks can be ascertained with but few clicks of the mouse.

Static problems in finite element analysis can be divided into two groups:

- Linear
- Non-linear

Linear static analysis deals with tasks in which the outcome of the calculation is linearly related to the original values. This way, where the force applied to the evaluated part will be decreased, the stress resulting from such change as well as displacement and other variations will be reduced proportionally. Where this rule cannot be applied, such analyses are considered *non-linear*. Lately, there are some advanced finite element analysis programs capable of solving assignments involving nonlinear materials like rubber, while others are still considering these as linearly elastic materials.

The FEA software can be used to perform design optimization studies, during which an existing design can be tested and evaluated for feasibility of production and for the given material's suitability. For example, a bent-up part can be evaluated for the smallest and the largest corner radius, this particular material would tolerate. The software takes into account all cutouts in the part and may even suggest a design change.

For the purpose of finite element analysis, the object to be analyzed is segmented, by the software, into small particles called finite elements, or in other words, it is being "discretized." In 2D objects, the finite elements can be triangles or quadrilaterals; in 3D objects, they can be tetrahedrals, or bricks of 8-nodes, up to hexagonal prisms. All the finite elements together are called a *finite element mesh.*

Discretization methods vary; there can be a finite difference method, boundary element method, finite element method, and others. Most of current linear analyses are using the boundary method, while nonlinear applications are leaning toward the finite element method. In structural mechanics, finite element method is the dominant technique of discretization.

The calculations, even though performed at the nodes only are very complex and may often contain thousands of linear algebraic equations. Still, these calculations are but approximations evaluating the displacement of each reference point under a load. From the distances these corner points become relocated, the stress and strain are calculated.

Approximation being the method of assessment, the accuracy of it becomes an issue. Naturally, dividing the analyzed object into smaller and smaller elements diminishes the error caused by approximation. But at the same time, we cannot diminish the segments of the mesh infinitely just to increase the accuracy of the calculations. The decrease of finite elements' sizes, also called a *mesh refinement process*, or convergence analysis, not only adds to the computing time, but further demands a tremendous amount of computer memory, making the given task much more complex with possibility of errors arising from numerical processes themselves.

Additionally, refining the mesh will not help in instances where there are errors contained in the basic model, or where the definition of task to be performed is vague. A correct evaluation of material's suitability should not be overlooked here either.

The basic form of a finite element is a bar (see Fig. 2-7). In a 1D method of representation, it may be a straight line or a curved line, and it may represent an actual bar or an I-profile, or some other strip of material. In 2D representation, the single line graduates into a rough, structure-representing shape.

Every finite element is defined by nodal points or nodes. These are located at the ends of each 1D element, or at corners of 2D and 3D representations and they define the

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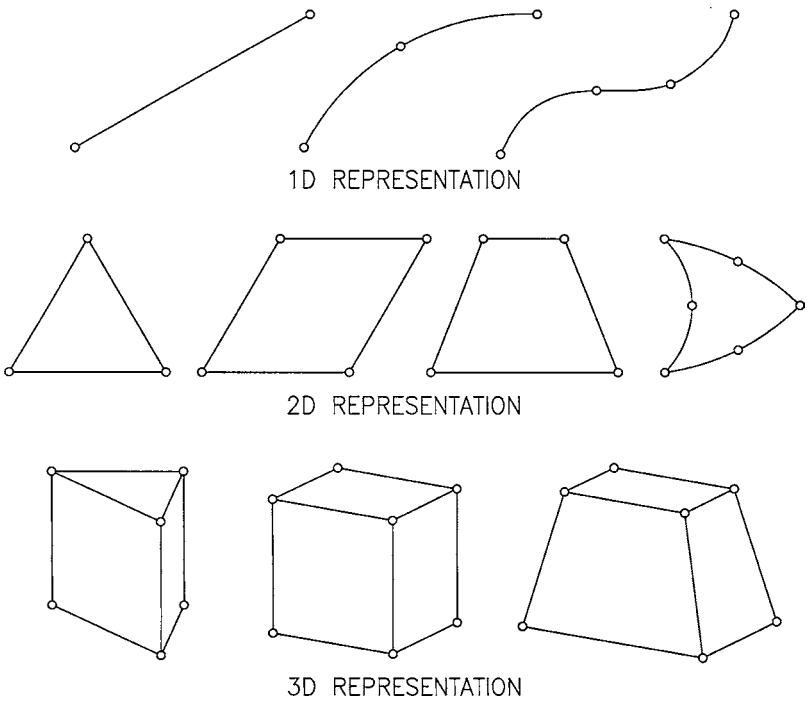

FIGURE 2-7 Methods of representation in finite element analysis.

element's geometry while controlling the amount of freedom of that particular segment. In higher-order elements, these nodes are also located on the facets of the part and in its interior.

There are two basic types of discretization used in most finite element analysis software nowadays. There is a method utilizing H-elements, where "H" represents the size of a particle, with P-elements utilized elsewhere. The main difference is the order of calculations, which are of lowest order for H-elements, with higher order calculations for P-elements.

Convergence Method Using H-Elements. Finite element analyses performing convergence with H-elements consider the stress evenly distributed throughout each finite element, which in itself can be the cause of many discrepancies. The coarseness of the mesh can be of additional hindrance here. The more crude the mesh, the more error-prone the convergence analysis will be (see Fig. 2-8*a, b*). Since we will not be able to restrict further refinements to the areas of interest only, but rather the whole mesh will be refined uniformly all over, we may not achieve a decrease of error due to approximation, and yet we will suffer the increase in calculating time.

Convergence Method using P-Elements. P-elements in this convergence method are interpolating polynomials of higher order (see Fig. 2-8*c*). Some software packages use an impressive order of nine as the highest. The mesh can consist of tetrahedrals, 4-node particles, or 8-node bricks, and often it can be quite crude, with refinement applicable to the areas of interest only. The accuracy of calculations is greatly improved by the higher order

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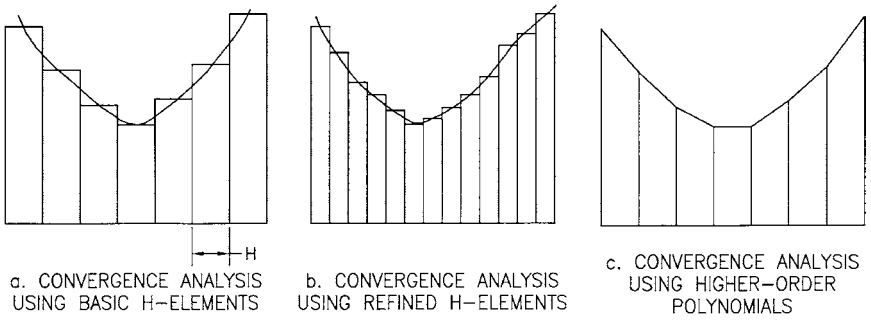
H
a. CONVERGENCE ANALYSIS USING BASIC H–ELEMENTS
b. CONVERGENCE ANALYSIS USING REFINED H–ELEMENTS
c. CONVERGENCE ANALYSIS USING HIGHER–ORDER POLYNOMIALS

FIGURE 2-8 Finite elements.

of polynomials: Where the H-element convergence method will need 16,000 nodes, P-element method can operate at 4000 with the same results.

The P-element method considers the stress to be linear throughout each finite element. A 3D tetrahedral element supports three translational levels of freedom per node and it can be nonlinear. It can be subjected to loading in the form of temperature, pressure, acceleration, and others. Finite element analysis is additionally capable of ascertaining the degree of isotropic hardening, plane strain, changes due to kinematic influences, and many other variables.

2-3 EXTERNAL INFLUENCES ON THE PART AND THEIR IMPACT ON PLASTIC DEFORMATION

Several factors may affect the process of plastic deformation of metal material by influencing the extent of deformation and the actual feasibility of the forming process along the given guidelines. Many of these factors are so tied to the forming process itself that they are inseparable from it, and yet their presence may bring about a total failure of that operation.

Widely known factors of influence are the hardness of the material, thickness and its variations, chemical analysis, and absence or presence of harmful or beneficial elements. These factors can be assessed long before the forming or drawing processes begin. However, there are influences that are difficult to ascertain, difficult to plan or predict, and therefore difficult to evaluate beforehand.

One of the basic influences on the part is the contact with the forming, drawing, or cutting tooling. Here, the type of material, the surface finish, the wear and tear of the tooling, and that of the part's surface can immensely affect the final result of that particular operation. Add the speed of the metal-forming process, the lubricant used or its absence, clearance between the functional surfaces of the tooling, to name but a few, and a whole "jungle" of variables emerge, ready to attack the manufacturing process and the resulting product.

The fact, that the process of forming, cutting, or drawing alone is capable of producing changes in the areas of contact between the tooling and the material can become further enhanced by changes in the distribution of stresses within that material, changes in the size of the formed part, and other changes does not always help either.

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2-3-1 Temperature

One of the important external influences to consider is the temperature of the manufacturing process. The fact that the crystalline structure of the part is being altered during plastic deformation triggers a rise in the crystalline energy. As previously confirmed by experiments, only about 10 to 25 percent of this energy outlay goes against the forming process itself. The rest of it is transformed into heat.

For this reason, the temperature of metals during the forming process is increased, which in itself allows for a division of forming processes into,

- Cold forming
- Half-warm forming
- Warm forming

All of these variations are taking place during specific temperature ranges. For example, heating an object to

$$0.2T_m \le T_w \le 0.3T_m \tag{2-12}$$

where T_m is the melting temperature and T_w is the working temperature; and keeping such temperature range for a prolonged time, which is followed by cooling produces changes in the substructure and ensuing changes in mechanical qualities of the material, such as lowering of hardness, lowering of the shear strength, and enhancement of plasticity.

Deformation with no subsequent loss of hardness of the material is called a *cold deformation* and its occurrence can be observed at temperatures of $T_w \le 0.3T_m$.

Additional increase of heat, up to $T_w \le 0.4T_m$ and remaining at such temperature level for extended period of time, which is followed by a slow cooling can somewhat revive the crystallographic structure of the material and give rise to newly-formed crystalline structures. This process is called *recrystallization*.

At half-warm forming, which occurs at temperatures of $0.5T_m \le T_w \le 0.7T_m$, the lowering of the hardness of material is obvious with subsequent relaxation and changes in its crystalline structure, or recrystallization.

With warm forming, or at $T_w \ge 0.7T_m$, the metal material loses all its hardness and the resistance to deformation disappears almost totally.

2-3-2 Forming Speed

Speed of the forming process is another important aspect that can affect the material and produce variations in the final outcome. Slow deformation during the cold forming process will have a noticeable influence on the material's resistance to forming. With increase in temperature and with increase in forming speed, the resistance to forming is often lowered.

However, a sudden increase in the forming speed during cold forming may increase the forming resistance of the material.

2-3-3 Changes in the Size of the Formed Part

During forming, not only the structural changes occur in the part, but additionally, modifications of the part's size can be observed. These changes depend on the size and geometrical

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shape of the deformed areas, which varies with the technological process used. The best indicator of such changes is the relationship of the length and width or, *l*/*w*.

Naturally, friction is an influential factor in this scenario and it can be said that the multiplying element of friction consists of the changes in the stress range in the part, changes of deforming influences, as well as changes in the hardness of material.

One of the basic elements of influence in the forming process is the forming force (i.e., forming intensity), as it is being transferred into the material by the tooling. Where such forming force is being completely absorbed by the formed material, as it happens in drawing, forming, and extruding, such influence can be expressed as:

$$P = P_r A \tag{2-13}$$

where P = forming force
P_r = forming resistance (formula below can be used)
A = area of contact

The material's resistance to deformation can be expressed as:

$$P_r = P_s + F_o + F_i \tag{2-14}$$

where P_s = deforming strength of the material. It is based on the properties of the formed material, on the stress/deformation state, on the degree of deformation, its speed, and temperature.
F_o = amount of stress due to the outer friction on the material, which is heavily influenced by the type of lubricant being used, the surface condition of the tool and that of the material, temperature, distribution of forming stresses in the areas of contact between the forming tooling and the material;
F_i = inner (complementing) friction, dependent on the geometric parameters of the area of deformation and on the type of transmission of the forming forces into the material.

2-3-4 Extent of Deformation and Strain Hardening

Strain hardening is a phenomenon that can be encountered during forming of metals at lower temperatures. Here the operation itself causes the crystals of the formed material to become more refined, while extending themselves in the direction of the forming force. The elasticity decreases and the hardness increases.

The initial deformation will always hinder all subsequent attempts at forming or deforming of a part. Every deformation of metal material produces, alongside the intended changes in the part's shape or thickness, a resistance against such deformation as well. This resistance is called strain hardening and it exerts greater influence on material with cold working, since the low temperature is not adequate to keep the material structure elastic.

Some processes, such as drawing, must utilize a relieving process (i.e., annealing) after certain number of drawing passes. Otherwise the inner resistance of the material structure to additional changes will render the existing tooling and often the existing tool force, useless. In other words, the material hardness will exceed its forming capacities.

Once strain-hardened, the part requires an increase in forming force to achieve additional forming. True, sometimes the influence of strain hardening can be partially alleviated by heat working of the part, which may not be always beneficial. This process may produce distortion of the material surface, and uneven distribution of inner stresses (especially in localized heating) coupled with a diminished accuracy.

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Other than in drawing, strain hardening is sometimes considered beneficial to the product because of its effect on the part's useful hardness, with subsequent increase in *tensile strength*. Often such influences may justify the use of materials of inferior qualities and count on cold working to bring them up to required or expected levels of hardness and strength.

Along these lines, press-brake tooling and perhaps some other bending tools, are rarely ever hardened, for the hardening operation (i.e., heat treatment) will distort their shape and grinding the distortion away may not always prove satisfactory. This is true especially where a too complicated punch and die are being utilized, their length adding to the complexity of a problem. Instead, the necessary hardness of such tooling is developed during its use, through work hardening or strain hardening of the material.

Generally, strain hardening increases the hardness and tensile strength of the material, while the ductility is decreased. Even tumbling and vibratory finishing can harden the surface of parts, not talking about *sand blasting* or *shot peening*. The latter two processes totally alter not only the material hardness by creating an effect similar to the case-hardening, but the visual appearance of the part as well.

2-3-5 Superimposition of Outer Influences

Not all materials are easily formable and some can hardly be formed, if ever. These materials, usually of impressive hardness and poor modulus of elasticity, cannot be altered using the traditional manufacturing methods. For these, some new types of forming applications have been developed, namely

- Forming at very high pressures
- Superplastic forming
- Cyclic deformation

2-3-5-1 Forming at Very High Pressures. This type of forming is a good and effective process used to enhance elasticity in the material even where such property is nearly nonexistent. Most often, hydrostatic forming is being used. During the forming stage the part is subjected to the influence of a liquid at extremely high ranges of pressure. Such force diminishes the density of dislocations within the formed material, while forcing them to remain in the close proximity of the walls of the substructure-forming grain. This gives them no chance at grouping together, while it is successfully hindering the development of microcracks.

Such method of forming can be used for other than forming applications too. For example, where bulging of the material exists, or an oilcan effect and other stress-related distortions are encountered, forming at high pressures, or rather flattening or sizing at high pressures, can adequately relieve the material, leaving it stress free, straight, and even. Yet, the use of such forming methods is not always feasible as it is tied to a high cost of an equipment.

2-3-5-2 Superplastic Forming. By superplasticity we mean the ability of metallic materials to extend in length 100 percent and even 1000 percent of its original size, without suffering any physical or structural damage. Superplastic deformation does not cause the material to crack or to fracture and sometimes even existing cracks do not propagate any further.

Structurally, *superplasticity* can be defined as an ability of the material to develop extremely high tensile elongations at elevated temperatures, while being subjected to the controlled amounts of deformation.

Metal materials generally do not tolerate high strains during deformation. With the addition of heat to the process, the detrimental effect of strain hardening is diminished and superplasticity

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can result. Some alloys behave superplastically, rather quickly. These are zinc-aluminum, aluminum-copper, tin-lead, and even some alloys of the iron-chromium-nickel range.

At present, there are two types of superplasticity recognized:

1. Superplasticity based on the outer conditions.
2. Superplasticity based on the inner structure of material.

The first type of superplasticity is reserved to polymorphous materials and it can be observed at certain temperature ranges, i.e., 1560–1670°F (850–910°C) and at very slow deformations, with forming force in the range of 290 psi (2 MPa).

Of interest is the second type of superplasticity. This can occur only in materials with a very finely grained microstructure, where the grain size is in the vicinity of but several micrometers (i.e., 1–5 μm). The mechanism of deformation consists of slippage along the outline of the grain and often a displacement of the grain boundary, while slippage of dislocations inside the grains can be observed as well.

Unfortunately, the tooling for such processes presents a problem, as not many tooling materials are capable of withstanding high temperatures at extended periods of time. For that reason, the tooling with selectively cooled portions is sometimes being used along with heat-resistant steels and ceramic materials.

Additional problem is being created by the inability of some materials to stop behaving superplastically after the deformation has ended. They remain partially superplastic even afterwards and display a marked tendency to creep later on.

2-3-5-3 Cyclic Deformation. Cyclic deformation is performed either with intermittent pressure or with some other kind of vibrating influence upon the formed material. It is used in cases where the detrimental influence of surface friction has to be eliminated. Types of cyclic deformation applicable to forming can be categorized as

1. Pulsing, with frequency of less than 10 pulses per second
2. Vibrating, with 10 to 15,000 pulses per second
3. Ultrasound, using more than 15,000 pulses per second

The superimposition of *pulsing vibration* on the metal material in cold forming, when the material is exposed to the tensions caused by forming, seems to reduce the yield stress within the material. The dislocations of material crystals seem to follow the pattern of linear defects, which are considered the main causes of plastic deformation. The reduction of friction provides the material with a uniform yield across its surface. This gives a possibility of an increase of the depth of drawing (up to 37 percent for deep drawing) and to forming at much lower pressures.

The most often used method is that of *low frequency vibrating forming*, with 10 to 300 (and sometimes 1000) cycles per second. As with all types of cyclic forming, this method too is characterized by marked changes in contact friction. The coefficient of friction is considerably lowered, sometimes down to a fraction of its original value. Additionally, the surface conditions are improved, the stresses within the material are relaxed, and the shear strength is diminished.

Second in usage comes the *ultrasonic forming or ultrasound*. It has been proven that the application of ultrasound in the form of high-frequency vibrations is capable of reducing the needed forming force, while increasing the amount of deformation per each pass. The quality and surface finish were found improved along with greater dimensional stability of the part and reduction of friction.

For example, in wire drawing, the influence of ultrasound is often directed toward the die, where it can be applied either coaxially or in a perpendicular fashion. In coaxial application

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the maximum reduction of the drawing force was achieved in instances, where the wire itself began to resonate along with its tooling. With perpendicularly applied ultrasound the die was observed to periodically shrink and expand in size, giving the final product a slightly elliptical shape. A considerable reduction of stress is common with this application, especially where the vibrations are applied to the wire and to the tooling as well. The reduction of stress reached 45 percent in steel and 35 percent in aluminum.

Drawing with ultrasonically agitated lubricants is another approach of similar nature. Here, not only the tool and the formed material are being exposed to the ultrasound, but the lubricant too. The ultrasound affects the lubricant in such a way that its dispersion over the given area improves, resulting in almost ideal hydrodynamic lubrication. And again, such approach lowers the amount of drawing passes, while keeping the die free from depositions of the drawn material. The surface of the part is improved and the wear and tear of the tooling is lowered.

In sheet-metal forming, the forming friction was also found reduced due to the application of ultrasound, with subsequent lessening of the wear and tear of forming tools. The required forming/drawing force was observed as being diminished and the tolerance ranges on the part refined.

The disadvantages of these process are but few, but of considerable impact. First of all, the cost of the sonic devices has to be evaluated, including the amount of its high-power consumption and high-energy losses. The fact that only highly trained personnel can use such equipment is another drawback, not talking about the answer to a question: "How does the ultrasound affect the personnel operating such equipment?"

2-3-6 Friction in Forming and Drawing

Friction in metal stamping can have many beneficial as well as detrimental effects on the tooling and quality of produced parts. It increases the surficial pressure between the tool and sheet-metal material, which results in deformation of both, with subsequent degradation of surface quality and wear of tooling. This increases the demand for press force, often considerably escalating its levels.

Since the area of contact between the part and its tooling constantly changes, the distortion and degradation of surface affects a widespread portions of both. The roughing effect on the surface of tooling causes the actual contact areas to diminish in size and become localized, which subsequently increases the frictional influences in each such segment, and a faster deterioration of the tooling and parts follows.

The heat along with the damaging effect of surficial pressure, tears out small portions of sheet-metal material, attaching it permanently to the tooling or elsewhere within the area of contact. Such small pieces are as if welded; they are difficult to remove and their presence further affects the quality of parts, their dimensional accuracy, and the condition of tooling. For example, the force needed to overcome friction during the backward extrusion of a cup was found to amount to approximately 40 percent of the total force exerted by the punch.

The problem of friction is quite complex and cannot be readily solved. On the other hand, some processes, such as metal forming depend on a certain amount of friction, the removal of which may not be beneficial to the forming process at all. In the absence of this friction, grave problems with material retention may emerge, which may result in parts that are perhaps impossible to form at all. Additionally, such a condition may generate a completely different set of forces acting against the tooling, which may produce such an inner strain within its material structure that an internal distortion and collapse may become unavoidable.

The only means of controlling friction are lubricants. Lubricating materials are capable of separating the adjoining surfaces by providing an isolated layer of completely different physical and mechanical properties between them. With different types of lubricants, different

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results can be achieved and control of frictional forces may thus be brought to almost perfection.

There are lubricants that are immune to higher temperatures, lubricants that tolerate extreme pressures, high-viscosity lubricants, low-viscosity lubricants, and other variations.

2-3-6-1 Types of Friction. In metal fabricating, various materials, in combination with different types of lubricants, or in the absence of the same, will generate three basic types of friction:

- *Static, or dry friction*—created between two metallic surfaces with no lubricant added. The friction mechanism depends on the physical properties of the two materials in contact. A metallic lubricant (for example, lead, zinc, tin, or copper) may improve this condition.
- *Boundary friction*—where two surfaces are separated by a layer of nonmetallic lubricant a few molecules thin. The shear strength of the lubricating material is low, resulting in low friction.
- *Hydrodynamic friction*—where two surfaces are totally separated by a viscous lubricant of hydrodynamic qualities. In such a case, friction depends strictly on the properties of the lubricant.
- *Combined friction*—or a mixture of the above conditions. This type of friction is the most frequently encountered in metal-forming processes.

Out of all metal-forming processes, only a few do not require any surface treatment or coating when it comes to friction. These are: Open-die-forming, spreading, some bending operations, and extrusion of easily deformable materials. All other metal forming depends on the use of proper lubricants. Even die forging requires a surface treatment of raw material; in this case for the protection of the die itself.

2-3-6-2 Lubricants. The lubricant's main duty is to diminish the influence of friction between the tooling and the material. Ideally, lubricants should also act as a coolant and thermal insulator, while not being causative of any detrimental action against the tooling or the material, the press equipment or the operator. The lubricant should not cause rusting of metal parts, and should be easily removable by some accessible means.

Lubricants are of utmost importance in forming and drawing processes, where these can be divided into two categories, based on the type of lubricants used:

- *Wet drawing or forming*, using mineral oils, vegetable oils, fat, fatty acids, soap, and water
- *Dry drawing or forming*, using metallic coatings (Cu, Zn, brass) with graphite or emulsions, Ca-Na stearate on lime, borax or oxalate, chlorinated wax or soap phosphate

In metal forming, the danger of entrapping the lubricant with the fast action of the tooling presents additional possibilities of surface deformation. Usually, areas affected by a restrained lubricant display a sudden roughness, often resembling a matte finish.

Lubricating Components. The actual process of lubrication is provided by several basic ingredients. These are:

- Mineral oils, which are petroleum derivates, such as motor oil, transmission fluid, and SAE-oils.
- Water-soluble oils, which are a combination of mineral oils, adjusted by an addition of other elements to become emulsifiable with water.
- Fats and fatty oils, most often of vegetable or animal origin, such as lard, fish oil, tallow, all vegetable oils, and beeswax.

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- Fatty acids, such as oleic and stearic acids, generated from fatty oils.
- Chlorinated oils, a combination of fatty oils and chlorine.
- Soaps, which are basically water-soluble portions of fatty acids, combined with the alkali metals.
- Metallic soaps, which are insoluble in water, such as aluminum stearate and zinc stearate.
- Sulfurized oils, or hydrocarbons, treated with sulfur.
- Pigments, such as graphite, talc, or lead. These are actually minute particles of solids, not soluble in water, fats, or oil. They are often supplied in a mixture of oils or fats, which provide for their retention and spreading.

These ingredients when added into but three groups of compounds form a metal-forming lubricant. These compounds are as follows:

- Base material, a carrier.
- Wetting or polarity agent.
- Parting agent, or an extreme-pressure agent.

For example, in drawing process, the carrier may be oil, solvent, water, or a combination of several compounds. The wetting agent often consists of emulsifiers, animal fats or fatty acids, or long chain polymers. The parting agent, where added, is chlorine, sulfur, or phosphorus. Also added may be physical barriers, such as graphite, talc, and mica.

It is expected of a lubricant to be able to control friction, prevent galling, dissipate heat, and reduce tool wear. The dissipation of heat depends on the function and properties of the carrier. All the additional qualities and properties depend on the other ingredients and on that particular lubricant's mechanism.

According to the lubricating mechanism, there are three basic types that are being used:

1. *Hydrodynamic lubrication, or fluid film lubrication*. This type of lubrication works well where the lubricating film is not disrupted by an increase in temperature or speed. It is efficiently used for lubricating of auto engines, but unfortunately, in metal stamping and metal forming it has not found an application yet.
2. *Boundary lubrication* occurs where the lubricant is combined with surfactants, also called wetting agents or polar additives. These become attracted to the surface of metal of the tooling and that of the sheet-metal material as well, acting as a protective layer of these surfaces. Surfactants can be soaps, their base carrier being fat, oil, fatty alcohols, and the like. This type of lubricant further benefits from its enhanced wetting capacities. Of disadvantage are the temperature-related functionality limits, which top off with 100°C, or a boiling point of water.
3. *EP lubricants* can be chemical or mechanical. In chemical EP form, chlorinated hydrocarbons are added to stamping lubricants, where they form protective metallic salts on the surface of the part and its tooling. During the stamping process, the heat of the operation forces the released chlorine to interact with iron and the resulting iron-chloride film becomes the actual lubricant. Where sulfur is used in the lubricating base (i.e., carrier), the chemical reaction produces an iron-sulfide film. Mechanical EP lubricants' additives are molybdenum disulfide and calcium carbonate. The disadvantage of this lubricant type lies in the buildup it leaves on the part and on the tooling, which can affect some sensitive portions of the tool and cause their breakage.

A fourth type of lubricating mechanism exists in the form of various combinations of the above-described three methods.

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Many materials used in the production of electronics are incompatible with the third, EP method of lubrication. With bronze, beryllium copper, or phosphor bronze materials, their surfaces do not respond well to these lubricants. Actually, where sulfur is being used, staining of some alloys may occur. For this reason, a boundary method of lubrication using a combination of chlorine and fatty materials is preferable.

According to their basic component, lubricants can be further divided into:

- Oil-based
- Water-based
- Solvent-based
- Synthetic
- Dry-film

Oil-based lubricants are useful for processes where high loads are present. These are petroleum-based lubricants and their applications include punching, blanking, coining, embossing, extruding, some demanding forming operations, and drawing.

Water-based lubricants may sometimes contain oils as well, with which they form emulsions. These lubricants are easier to remove from the surface of parts than those based on petroleum. Lately this type of lubricating approach is becoming quite popular, since the performance of some heavy-duty types are on par with petroleum-based products. Water-based lubricants are well suited for progressive dies, transfer presses, and for drawing operations.

Solvent-based lubricants are of importance where the basic sheet-metal material is already coated, such as vinyl-coated materials, lacquered and painted surfaces, or laminates. In some instances, these lubricants do not require any cleaning nor degreasing afterwards, for which advantage they are preferred for manufacture of appliances, electrical hardware, and similar components.

Synthetic lubricants are very easy to clean, as they usually consist of solutions of chemicals in water. These can be used on coated surfaces, with vinyl-clad parts, painted parts, or aluminum. Many synthetic lubricants are biodegradable and as such they do not possess any environment-harming qualities.

Dry-film lubricants previously consisted of high melting point soaps. Some new types that emerged on the market are synthetic esters and acrylic polymers. These produce good results where applied to blanks or strips of sheet-metal material. Of a distinct advantage is their cleanliness, ease of handling and performance. Unfortunately, their cost is not always compatible with the requirements of the metal stamping industry, which is further complemented by their inability to dissipate heat of the operation.

As a rule, with all lubricants, their use and methods of application must be compatible with those they were developed for. Where a wrong lubricant should be used, the results of such manufacturing operation may be pitiful. Therefore, the lubricant's characteristics must be fully understood and tried out prior to production, to make sure these will be used only for processes they were intended for.

2-3-6-3 Lubricants as a Detrimental Influence. Not all manufacturing processes benefit from lubrication. There are instances where increase of lubricant will produce greater damage than its removal. A careful study of each situation must be made in all cases.

For example, drawing a cup while restricting the flange with blankholder (see Fig. 2-9) may produce tearing of the corner radius. Where such a situation exists, we must first ascertain if the blankholder's pressure is not excessive, so that it does not prevent the material from flowing. The friction between the part and the blankholder is of essence as well: Too often the addition of friction-lessening lubricant can produce harmful effects to the forming process.

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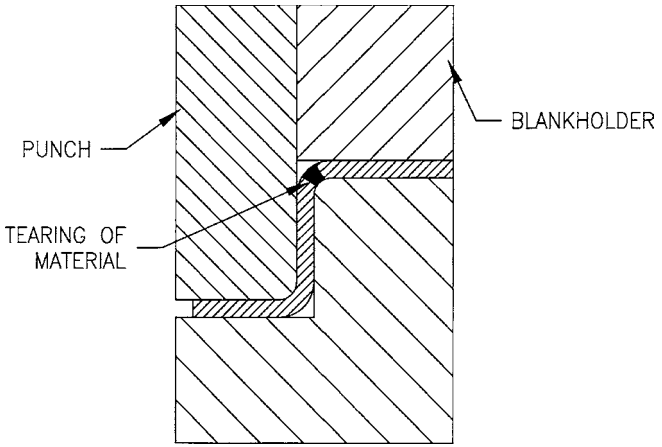

FIGURE 2-9 Failure in a formed part.

Next, our attention should be directed toward the space between the punch and the die, and between the punch and the blankholder. Finally, the forming radii have to be evaluated for their adequacy with regard to the material being formed. Often increasing the punch radius and roughing its surface, combined with the removal of all lubricant, can solve the problem.

As shown in Fig. 2-10, the excessive pressure of the blankholder, combined with forces of friction, can prevent the flange from flowing freely. This scenario can be expressed as

$$F_f = f(P_B) \tag{2-15}$$

where F_f = frictional force between the blankholder and the formed flange, or that between the formed flange and the die
f = coefficient of friction
P_B = force of the blankholder

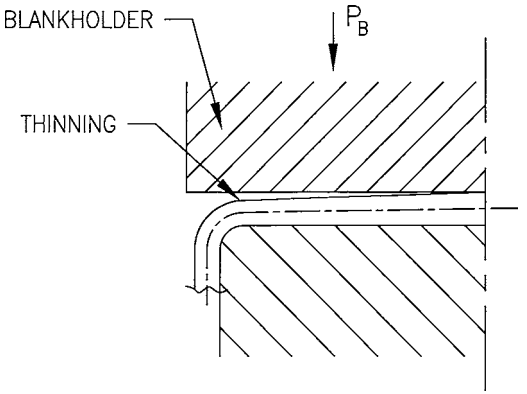

FIGURE 2-10 Blankholder's pressure and its influence on the formed part.

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2-4 SHEAR OF METAL IN CUTTING OPERATION

During any metal-cutting operation, the material is compressed between the punch and die until parted by the act of shearing. These forces against the material are not the only acting forces encountered. In parallel with the law of action/reaction, the material puts forth forces against the tooling as well. One of the major venues of material's influence aside from friction, is the *side thrust*.

When the punch hits the sheet-metal material, it first elastically extends the grain of the metal, forcing it to swell up, while pulling a portion of it from underneath the punch. Some of this swelling progresses downward too, and it remains tightened around the walls of die opening. The upper swelling wraps around the punch, impairing its withdrawal, sometimes breaking the tool where too thin a punch is used to penetrate heavier material. For this reason we should never forget that the minimum diameter of the punched/pierced opening should be at least 1.5 of material thickness with regular punches, and 1.1 to 1.2 thickness with guided tooling.

2-4-1 Side Thrust in Die Work

The side thrust force should not be taken lightly. With dependence on the punch size and the clearance between the tooling, and with regard to the sheet thickness and material strength, the amount of side thrust may often be in the vicinity of 0.02 to 0.18 percent of the blanking force. A formula to estimate such force is as follows:

$$P_{TH} = \frac{c(P_{BL})}{t - p} \tag{2-16}$$

where = P_{TH} thrust force
P_{BL} = blanking/piercing force
c = punch and die clearance
t = material thickness
p = depth of cut, usually, $0.5t$ to $0.6t$

The withdrawal force is similarly dependent, mainly on the punch size and on the clearance of the tooling. With greater diametral sizes, the withdrawal force diminishes. Generally speaking, the withdrawal force was found to be 0.01 to 0.05 percent of the blanking force.

2-4-2 Metal-Cutting Process

Following the penetration of the metal, the development of tensile and compressive stresses accompanied by subsequent changes of the part's edges, causes the material to separate (Fig. 2-11). There are several stages in the metal-cutting process, during which the transformation of material takes place, as shown in Fig. 2-12. An explanation is necessary, in order to understand the behavior of a sheet under the punch:

In Fig. 2-12*a*, clearance between the punch and die is clearly visible, and its amount is crucial to the success of the metal-cutting process. Clearance is the space between the two cutting edges, those of the punch and those of the die (see Fig. 2-13 for explanation of clearance influence). Clearance not only allows for the body of a punch to be contained in the cavity of a die; it also provides for the development of fractures during the cutting process.

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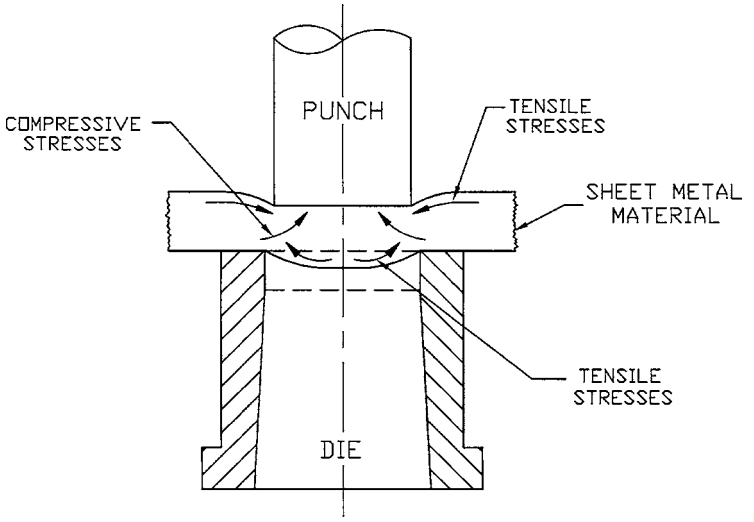

FIGURE 2-11 Stresses in shear operation.

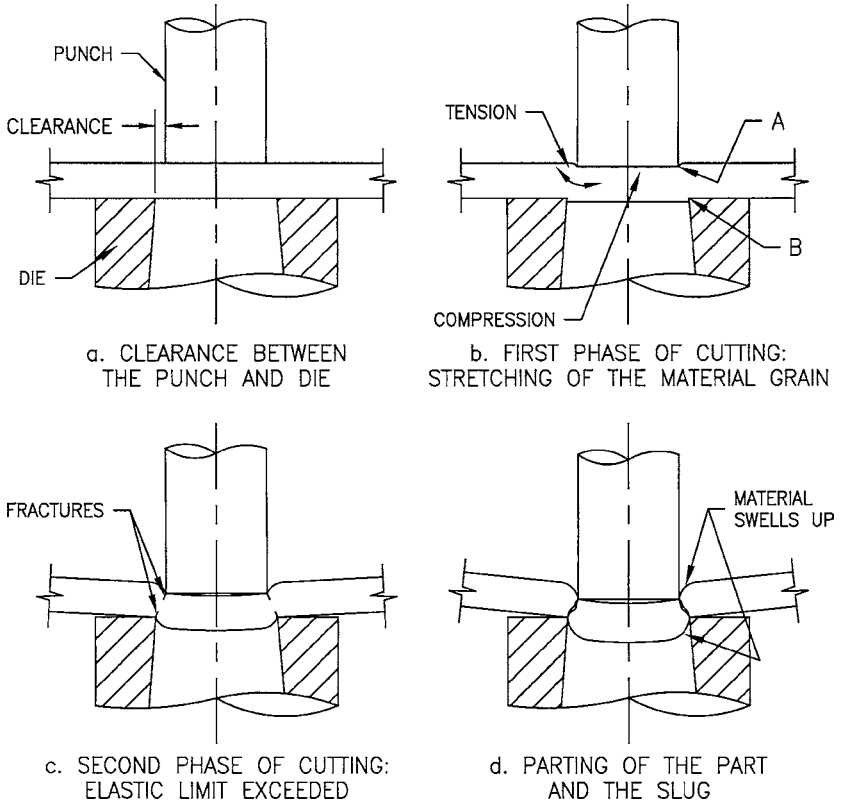

FIGURE 2-12 Effect of shear in piercing operation.

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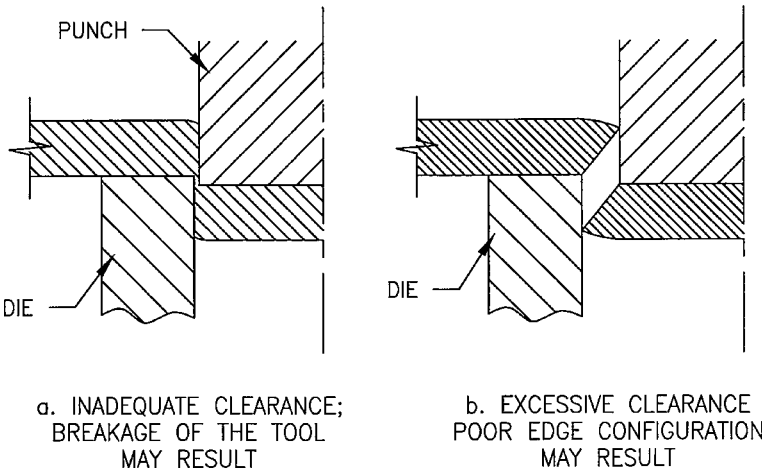
PUNCH
DIE
a. INADEQUATE CLEARANCE; BREAKAGE OF THE TOOL MAY RESULT
DIE
b. EXCESSIVE CLEARANCE POOR EDGE CONFIGURATION MAY RESULT

FIGURE 2-13 Effect of clearance on the contour of a pierced edge.

In Fig. 2-12*b*, the punch moves down and forces its way into the material. Stretching occurs at points *A* and *B,* where the stock is in tension; the remaining material under the punch is compressed. However, the material's elastic limit has not been exceeded yet.

In Fig. 2-12*c*, the punch pushes further down, and fractures begin to form around the corners of both punch and die as the elastic limit of the material is being exceeded. The angle of these fractures depends on the die clearance. If the clearance is either excessive or too small, this angle may not allow for a smooth connection of the upper and lower fractions, and a rough, jagged-cut may result.

In Fig. 2-12*d*, with further descent of the punch, fractures deepen and finally meet. The cutout is separated from the strip and pushed into the die. There, owing to inner stresses thus created, it swells up; the strip also tightens around the punch prompted by forces from within.

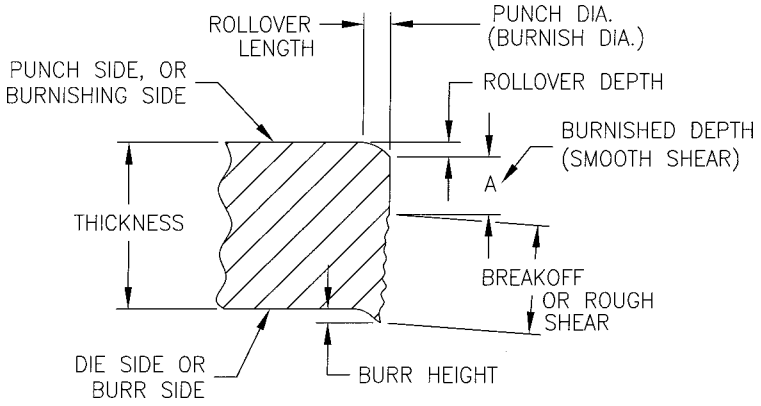

FIGURE 2-14 Detailed view of a pierced edge. (*Technical illustration is reprinted with permission from Dayton Progress Corp., Dayton, OH.*)

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TABLE 2-1 Shear Clearance Effects

	Shear clearance per side			
	5%	9%	12.5%	18%
Rollover length	0.0136	0.0101	0.0121	0.0138
Rollover depth	0.003	0.0035	0.0045	0.0056
Burnish depth	0.021	0.015	0.014	0.015
Burnish dia.	0.1875	0.1877	0.1879	0.1878
Burr height	0.0005	0.0006	0.0005*	0.0012

*0.0005 in. burr height was a result of providing 0.004 in. radius on the punch, to simulate "average" production run.

Note: 1. All values are in inches.

2. Test results above were recorded using 0.0275 in. thick CRS, HRb = 59 Punch diameter used: 0.1875 in.

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The fractures actually span through the area of tolerance from the edge of the punch to the edge of the die. The final cut's edge looks like that pictured in Fig. 2-14. From Fig. 2-13 it is obvious that the clearance between the punch and die has a major effect on the punching, piercing, perforating, or blanking operations. Usually, a 6 to 8 percent of the pierced material thickness per side is recommended with ordinary tooling (see Table 2-1). More information on specific tooling and its tolerances will be added later.

In Fig. 2-14, notice the smooth, straight, circumferential band (A), usually about one-third of the total material thickness (t) with well-sharpened tooling. The remaining two-thirds of the stock thickness are called the breakoff. The upper surface is called the *burnishing side, or punch side*, and the bottom is the *burr side.* In every punching, piercing, or blanking operation, the burr side is always opposite the punch.

The proper identification of the burr side is of great importance in some secondary operation such as shaving, blanking, and burnishing. Also the visual appeal and the functionability of the part may be ruined should the burr appear at the wrong side.

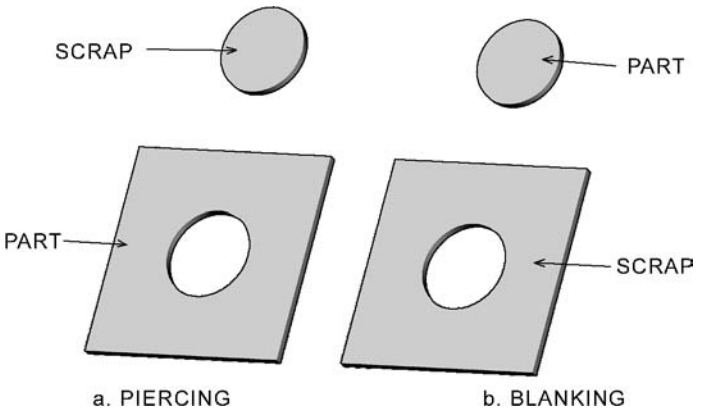

FIGURE 2-15 The difference between piercing and blanking operation.

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All these aspects have to be combined with yet another criteria, that of the desired part's selection (see Fig. 2-15): Is it the round cutout just ejected through the die? Or is the remaining portion of the sheet-metal strip or blank the final product? These are important questions to ask first, before resorting to the final die layout, or when troubleshooting.

2-5 BENDING AND FORMING OF SHEET METAL MATERIAL

During simple bending, sheet-metal material remains homogeneous and isotropic. No stress residues remain within its mass on termination of a simple bending process.

Generally speaking, there are various bending methods, which include stretch forming, also called wrap forming, roll forming, forming with high pressures, rubber forming, to name but a few. In die work, majority of bending operations can be divided into four types:

- V-die bending
- U-shape bending
- Wipe bending
- Rotary bending

2-5-1 V-Die Bending

V-die bending is shown in Fig. 2-16. The first example is that of a regular V-die bending, with bottoming at the downstroke of the press. At that moment, the material is ideally forced to fill the gap between the punch and the die and it seems that aside from springback nothing can alter a perfect bend. Actually, as with every manufacturing process, there are many variables involved, each of them capable of rendering such optimistic expectations wrong. There is the material thickness to compensate for, the speed of the operation, the method of edges' cutoff and the resulting development of cracks, the radius of the punch, breakage of tooling, and other agents of influence. Where the strip is too narrow (Fig. 2-16*c*), a shift during the downward stroke is possible. This usually happens at the moment the material cannot be guided by almost any means but pins, as shown Fig. 2-16*d*. Of course, where pins are used to restrain the part in its location, the material will certainly pull on them; that has to be anticipated.

In V-die bending with so-called bottoming, the material does not have to hit home in the area of bend radius. Actually, a sharp corner in the die, as shown in Fig. 2-16*a*, or even a relief slot (Fig. 2-16*c*), can be of advantage there. Anyway, the formed material will always wrap around the punch and have no tendency whatsoever to fill that sharp corner.

Actually, to add a corner radius to the V-die may be quite disadvantageous, as the distance between its surface and that of the radius of the punch becomes crucial to the outcome of bending. A slight deviation in the material thickness, or a slight buildup on the punch or die, and the bend may end up in a failure. Coining that may occur in such a situation may also be highly detrimental to the tooling.

The second version of V-die bending (Fig. 2-16*b*) is so-called air bending. The term air bending refers to the fact that the punch does not bottom with the downstroke of the press. Such bending offers the advantage of a variation of the bend angle, including the

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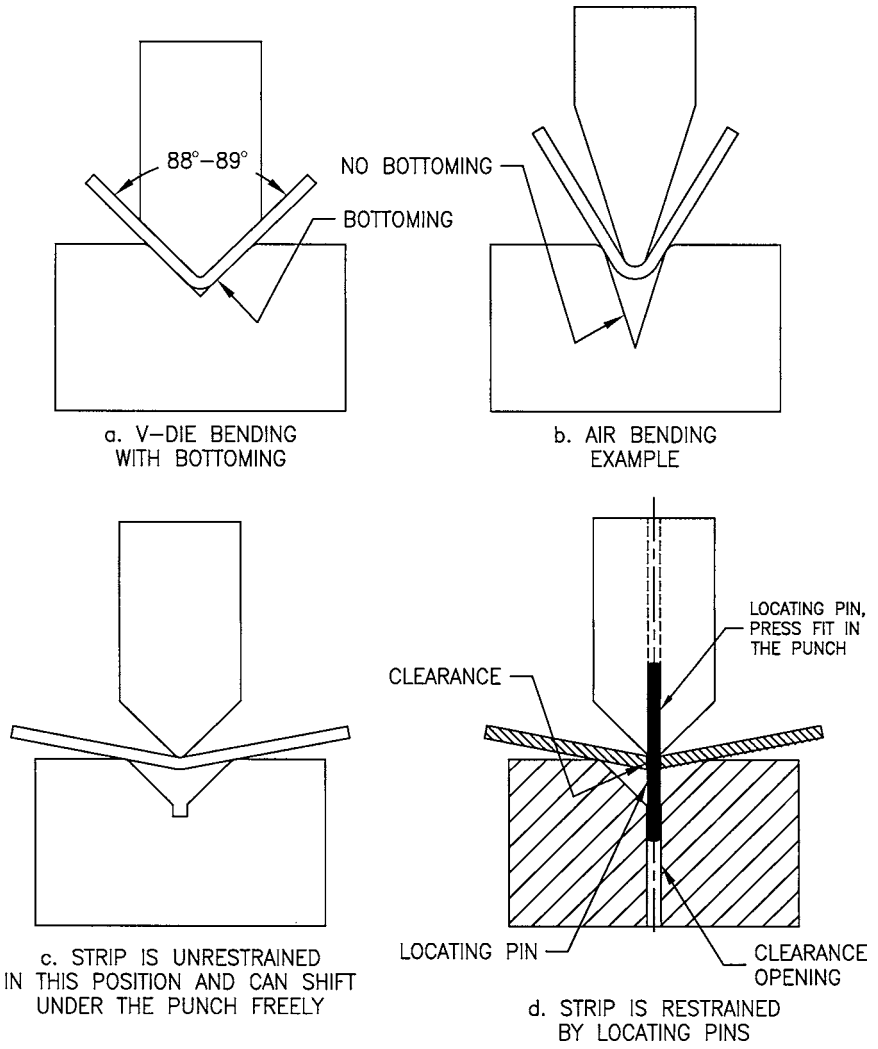
88°–89°
BOTTOMING
NO BOTTOMING
a. V–DIE BENDING WITH BOTTOMING
b. AIR BENDING EXAMPLE
c. STRIP IS UNRESTRAINED IN THIS POSITION AND CAN SHIFT UNDER THE PUNCH FREELY
LOCATING PIN, PRESS FIT IN THE PUNCH
CLEARANCE
LOCATING PIN
CLEARANCE OPENING
d. STRIP IS RESTRAINED BY LOCATING PINS

FIGURE 2-16 V-die bending, air bending, and bottoming.

possibility of overbending. The bend angle is controlled by the length of the punch travel. Bends produced by this process may suffer from a slightly greater springback. Also, the narrow body of the punch is more prone to damage.

Both types of V-die bending allow for overbending, which means that the bends under 90° can be produced. This is attainable by making the angle of the punch tip sharper, often along with a corresponding angle of inclination applied to the die where boltoming is required. Habitually, the V-die punch tip for 90° bends is produced with a 88° to 89° angle, which is what, in the majority of cases, the springback most often amounts to.

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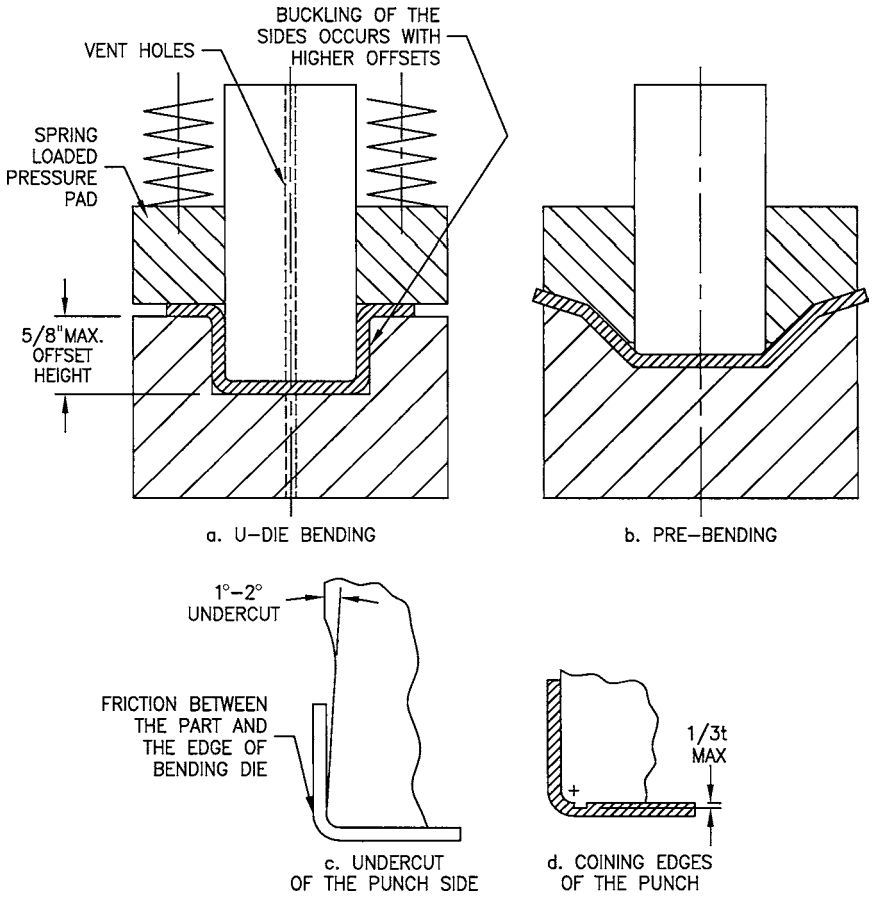
BUCKLING OF THE SIDES OCCURS WITH HIGHER OFFSETS
VENT HOLES
SPRING LOADED PRESSURE PAD
5/8" MAX. OFFSET HEIGHT
a. U–DIE BENDING
b. PRE–BENDING
1°–2° UNDERCUT
FRICTION BETWEEN THE PART AND THE EDGE OF BENDING DIE
c. UNDERCUT OF THE PUNCH SIDE
1/3t MAX
d. COINING EDGES OF THE PUNCH

FIGURE 2-17 U-die bending.

2-5-2 U-Shape Bending

U-shape bending (see Fig. 2-17) can be produced in a single hit up to a certain height only. This height, $^1/_2$ to $^5/_8$ in. (12 to 16 mm), which depends on the material thickness, cannot be exceeded, otherwise the sides of the part will buckle or collapse. In order to achieve deeper U-shaped bends, prebending is absolutely necessary. Deeper U-shaped bending arrangements may need to be provided with spring-loaded ejection of the parts (not shown).

Also of concern is vacuum, which may develop between the punch or a die (or both), and the part. For removal of trapped air/vacuum, vent holes through the tooling should be provided (see Fig. 2-17*a*).

A definite disadvantage of this process lies in its limited applicability to 90° and shallower bends. It is nearly impossible to obtain sharper-than-ninety bend this way, which can be so useful when compensating for the springback of material. Sometimes, with dependence on the type of material used, the two methods described below can be utilized.

The first method uses an undercut on the punch, hoping for a slight drawing action (due to friction) between the formed material and the edges of the die cutout (see Fig. 2-17*c*).

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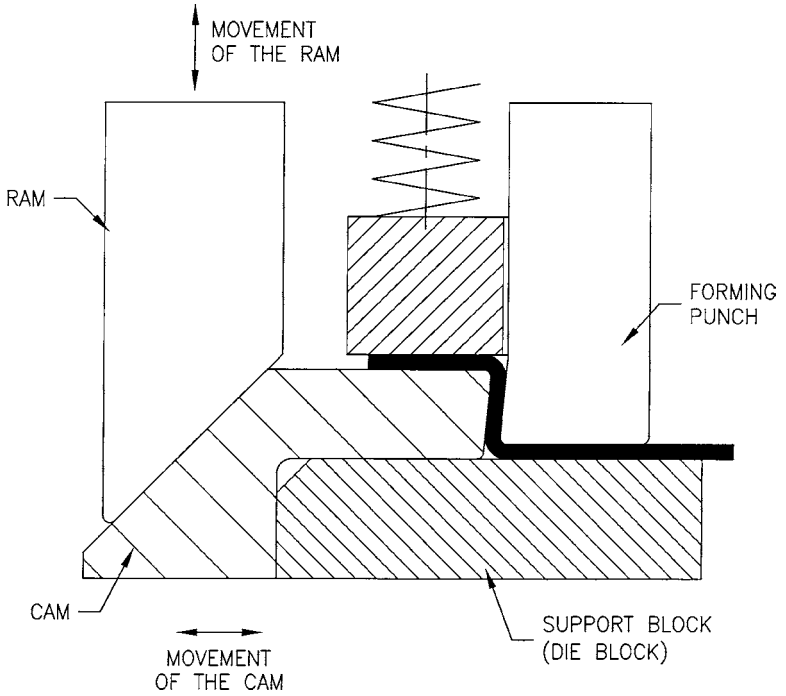

FIGURE 2-18 Cam mechanism, simplified.

This type of forming process forces the flange somewhat toward the body of the punch, possibly exceeding the 90° limitation by slight overbending. The springback that follows relieves the U-shape enough for easy stripping off the punch. Of course, care must be taken not to relief the tip of the punch too much, for it may collapse during usage.

The second method consists of producing small strips of protruding material on the face of the punch, right after the center of radius, as shown in Fig. 2-17*d*. These small, few thousandths high protrusions will not impair the action of the bending radius of the punch. At bottoming they will dig into the formed material and coin a narrow strip in it. Such coining may often secure the bend enough, so that it will not experience much springback afterwards.

There is, of course, a cam movement, which can always be resorted to, to solve the problems with the springback of material, but at a cost. A simplified cam mechanism is shown in Fig. 2-18. Here a cam is pushed forward by the descending ram. It moves toward the forming punch and toward the material being formed. Afterward, it serves as a support for the spring-loaded pressure pad, which forms the flange.

Timing is of essence in this process. The cam must be in its place soon enough to offer the needed support to the pressure pad, yet it should not push all the material all the way, as the descending pressure pad will have a hard time to grab and form the flange should that be sticking upwards. The pressure pad should not descend down too readily either, as it may buckle the flange. A dwell in the press action may be needed here.

When retracting, the ram is going up, which relives the cam of its forwarding pressure. At that point, the cam must be pulled away from the punch by a spring action (not shown in the illustration).

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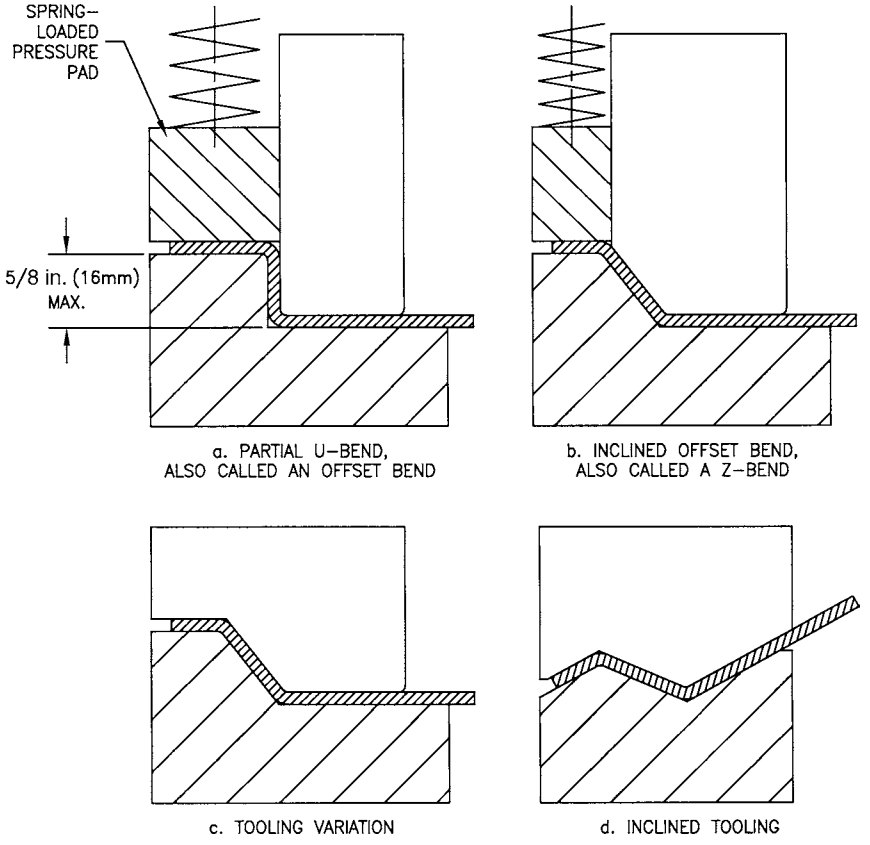

FIGURE 2-19 Partial U-bend, or an offset bend.

The mechanism of any cam movement is intriguing, but costly. The blocks must have a perfect surface finish, so that they slide over each other with ease. The proper hardness of various segments of the assembly is important too. For these reasons and for its complexity, cam movements are resorted to only after everything else failed.

2-5-3 Offset Bend and Slanted Offset Bend, or a Z-Bend

These are variations of a partial U-bending, as shown in Fig. 2-19. This type of a bend involves only one-half of the U-shape, and it is often called an *offset bend*. Where the horizontal leg is inclined (Fig. 2-19*b*), a "Z-bend" term is sometimes used. All the advantages and disadvantages of the U-bending are present here along with the limitation on the height of the vertical leg. Of advantage may sometimes be the inclined bending, Fig. 2-17*d*, which often solves the problems with the positioning of material under the punch, especially where press-brake type of bending is being used.

Sometimes, rubber or urethane forming inserts are resorted to, in a hope that the elastic qualities of these materials will allow for a better action of the forming punch. Yes, these enhancements often work quite well. Unfortunately, the wear of the elastic material can be excessive and may drive the price of such arrangements sky high.

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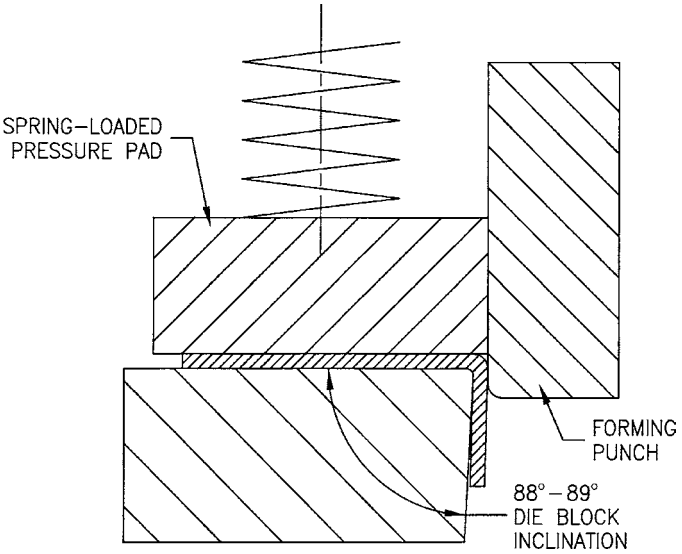

FIGURE 2-20 Wipe bending.

2-5-4 Wipe Bending

Another bending approach is that of wipe bending (see Fig. 2-20). This is old method of bending, which most probably developed from retaining a piece of sheet metal in a vise, while hammering the exposed flange to an angle. Wipe bending is a simple process, the tooling for which is easy to produce. But this type of bending does not allow for any marked overbending and additionally, the punch may sometimes leave heavy scoring marks on the surface of the part. Still and all, a great portion of bending is done using this method, since the advantage of the part's retention before actual bending takes place cannot be overlooked.

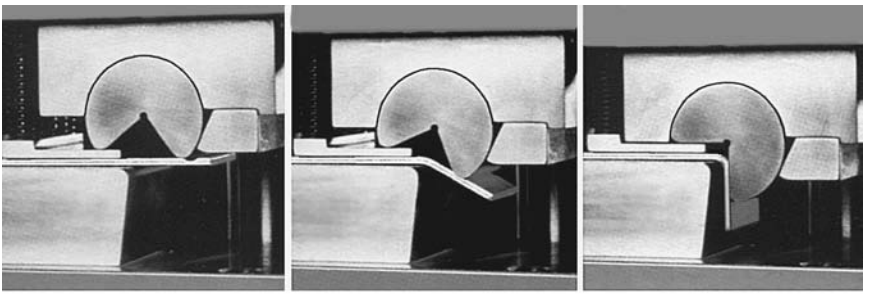

FIGURE 2-21 Sequence of rotary forming motion. (*Reprinted with permission from Ready Technology Inc., Dayton, OH. Patent Number 5,404,742.*)

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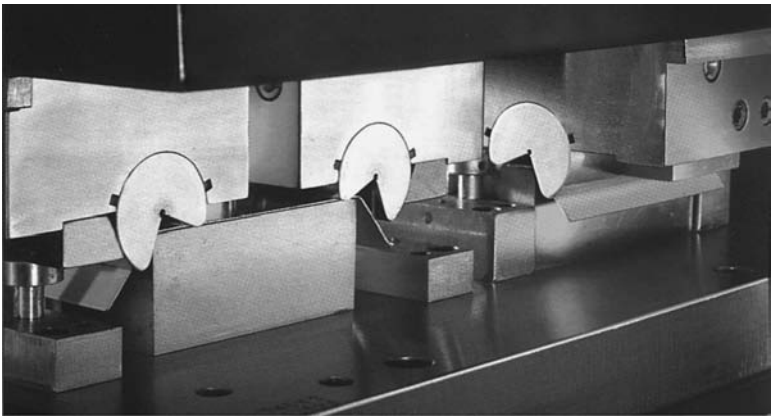

FIGURE 2-22 Ready Benders® as assembled in a die. (*Reprinted with permission from Ready Technology Inc., Dayton, OH. Patent Number 5,404,742.*)

2-5-5 Rotary Bending

In rotary bending, the scoring of the surface by a punch is diminished to a minimum. This is a newer type of bending process, which uses rockers to produce a bend. Overbending is easy, as shown in Fig. 2-21. In Fig. 2-22, Ready Benders® are shown as assembled in a progressive die.

2-6 MOVEMENT OF METAL IN BENDING AND FORMING, AND AXIS' SHIFT

In forming, as in bending, there is always one boundary of metal stretched and the opposite one shrunk. In between, somewhere around the middle of the stock thickness as shown in Fig. 2.23, there is an imaginary axis, which is considered neutral. Some believe it to be exactly in the middle, others place it in one-third, and the rest uses a host of additional ratios.

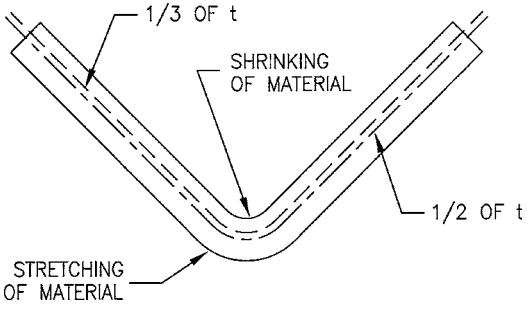

FIGURE 2-23 Neutral axis in bending operation.

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Similarly, various calculations differ in approach to the location of neutral axis, as well as in results. Many times the condition of tooling, or the prevailing methods used within the particular shop, material variables, and the like, render all such formulas unsuitable. Therefore, with sensitive parts, where the blank dimension is difficult to assess, or when working with an unknown material, it is advisable to construct few temporary punches and dies, and run tests, recording the results and comparing them to previously performed calculations.

In bending, as in forming, the size of the bend radius is of great importance. Often a drawing may call for a sharp-corner bend, which someone put down without realizing that such bends are virtually impossible to obtain. After all, if sheet metal were forced into such a bending extreme, it would be cut. The existence of some corner radius is absolutely necessary, and the greater in size, the easier the bending process is, up to certain limits in its size. The smallest bend radii per different stock thicknesses and material types are discussed in Chap. 8.

Forming, even though similar to bending, differs in that it adds some drawing action to the process. Forming utilizes the plastic capacities of the material in a wide range of applications. Mill-rolling, extruding, heading, drop forging, and even drawing, swaging, spinning, and bulging can all be considered metal-forming operations.

Regarding the formed material's mechanical properties, forming processes can be divided into three basic groups:

- Unaltered
- Temporarily altered
- Permanently altered

This classification is based on elastic limits of various materials. Further division can be obtained by sorting all forming processes with regard to the distribution of stresses in the material as:

- *Tensile forming*, where the deformation is achieved by application of various singular or multitudinal tensile stresses. Examples of such forming are stretch forming, stretch drawing, bulging, expanding, and embossing.
- *Compressive forming*, where the alteration of the part is achieved with the aid of various compressive forces acting upon it. This type of forming is represented by coining, forging, rolling, heading, plunging, and swaging.
- *Tensile and compressive forming combined*, which include metal spinning, deep drawing, ironing, some types of bulging, and flange forming.

2-7 VARIATION OF STOCK THICKNESS IN BENDING AND FORMING OPERATIONS

In any type of metal-altering processes, the variation in cross-section of the sheet-metal material is in direct proportion with the following influences of the

- Condition and construction of tooling
- Friction between the tooling and the strip
- Compressing forces against the surface of material
- Influence of material's own mechanical properties

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In bending, should the die surface be rough or should the clearance between the punch and die be inadequate, there will be some amount of drawing produced right within the bend or in its immediate proximity. This, in turn, may cause accumulation of material elsewhere, accompanied by bulging, buckling, and other defects. Such modification of the process is mostly undesirable, as it also changes the material's cross-section, which in turn influences the size of the finished part.

The material is already predisposed to differences in the outcome of various operations because of its grain structure. An additional distortion in thickness may only add to problems and discrepancies.

As mentioned earlier, in simple bending, the material is shrunk on one side of the bend and stretched on the opposite side. However, the amount of this variation is not consistent with all types of bends and materials. Thinner stock and smaller radii will bring about different-sized parts than thicker stock with larger radii.

Therefore, we may generalize that a bent-up part's final dimensions depend on the radius of the bend with regard to stock thickness. For example, material 0.031 in. (0.79 mm) thick with inner bend radius of 0.062 in. (1.57 mm) decreases in length after bending some –0.007 in. (0.18 mm) per bend; the same material with 0.125 in. (3.18 mm) bend radius will decrease –0.034 in. (0.86 mm) per bend. (For bend radii allowances, see Chaps. 7 and 8).

But not all material thicknesses and radii sizes decrease the linear length of the part. For example, material 0.062 in. (1.57 mm) thick with an inner bend radius of 0.062 in. (1.57 mm) will increase in length after bending approximately +0.016 in. (0.41 mm); stock 0.125 in. (3.18 mm) thick at a 0.125 in. (3.18 mm) bend radius will increase +0.025 in. (0.64 mm).

It seems obvious that the amount of compression or elongation of the bent-up material varies and therefore the neutral line (refer to Fig. 2-23) cannot be positioned in the middle of the stock. Rather its location will vary along with the thickness of the material and bend radius, while heavily influenced by the forming process used.

In a drawing operation, where the sheet metal's flat shape is deformed into a cuplike profile, all its available thickness is used up during such a transformation. Depending on the depth of the draw, the metal logically must get thinner and thinner, up to a complete fracture, tearing, and distortion, should the process continue. The opposite of metal thinning is its increase in thickness, which can be observed in some drawing operations where wrinkles and folds are formed.

With coining, necking, forging, and similar work processes, a portion of the part may get thinner, while its other portions will expand. However, such processes where the material is restricted from free movement by the shape of a die, display a more or less controlled form of thinning and thickening of stock.

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CHAPTER 3
METAL STAMPING DIES AND THEIR FUNCTION

3-1 DESCRIPTION OF A DIE

A die set is the fundamental portion of every die. It consists of a *lower shoe*, or a *die shoe*, and an *upper shoe*, both machined to be parallel within a few thousandths of an inch. The upper die shoe is sometimes provided with a shank, by which the whole tool is clamped to the ram of the press. Because of their much greater weight, large dies are not mounted this way. They are secured to the ram by clamps or bolts. However, sometimes even large die sets may contain the shank, which in such a case is used for centering of the tool in the press. Figures 3-1 and 3-2 show the basic components of a compound and a progressive die.

Both die shoes, upper and lower, are aligned via *guide pins* or *guide posts*. These provide for a precise alignment of the two halves during the die operation. The guide pins are made of ground, carburized, and hardened-tool steel, and they are firmly embedded in the lower shoe. The upper shoe is equipped with bushings into which these pins slip-fit.

The *die block*, containing all die buttons, nests, and some spring pads, is firmly attached to the lower die shoe. It is made of tool steel, hardened after machining. The die block is usually a block of steel, either solid or sectioned, into which the openings are machined. The openings must match the outside shapes and outside diameters of the die bushings; they must be precise and exact, since the die bushings are press-fitted into them. A relief pocket must be provided for headed bushings' heads.

The *punch plate* is mounted to the upper shoe in much the same manner as the die block. Again, it is made of a hardened-tool steel, and it may consist of a single piece of steel, or be sectioned. It holds all punches, pilots, spring pads, and other components of the die. Their sizes and shapes conform to tooling they must contain minus the tolerance amount for press fit.

Both the die block and the punch plate are often separated from the die shoe by *back-up plates*, whose function is to prevent the punches and dies from becoming embedded in the softer die shoe.

The sheet-metal strip is fed over the die block's upper surface, and it is usually secured between *guide rails* or *gauges*. There are two types of gauges: *side gauges*, for guiding the sheet through the die, and *end gauges*, which provide for the positioning of stock under the first piercing punch or blanking punch at the beginning of each strip.

The strip is covered up, either whole or its portions, by the *stripper*, which provides for stripping of the pierced material off the punch. The stripper is usually made from cold-rolled steel, and its openings are clearance openings for the shapes of punches. Where bushing are provided for a more positive guidance, press-fitted method of their insertion is often used.

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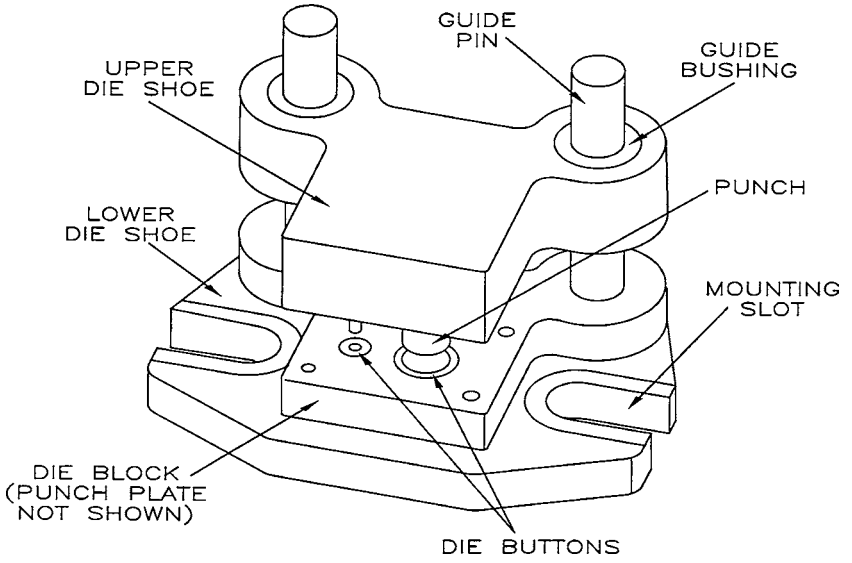

FIGURE 3-1 Compound die.

The *stationary stripper* is mounted to the upper surface of the die block with a strip-retaining channel running its entire length. The *spring-loaded stripper* is held in an offset location by the force of springs, and in such a case it is attached to the punch plate.

With reverse punching, where the punch is mounted in the die block and the die is up in the punch plate, the stripping arrangement is reversed.

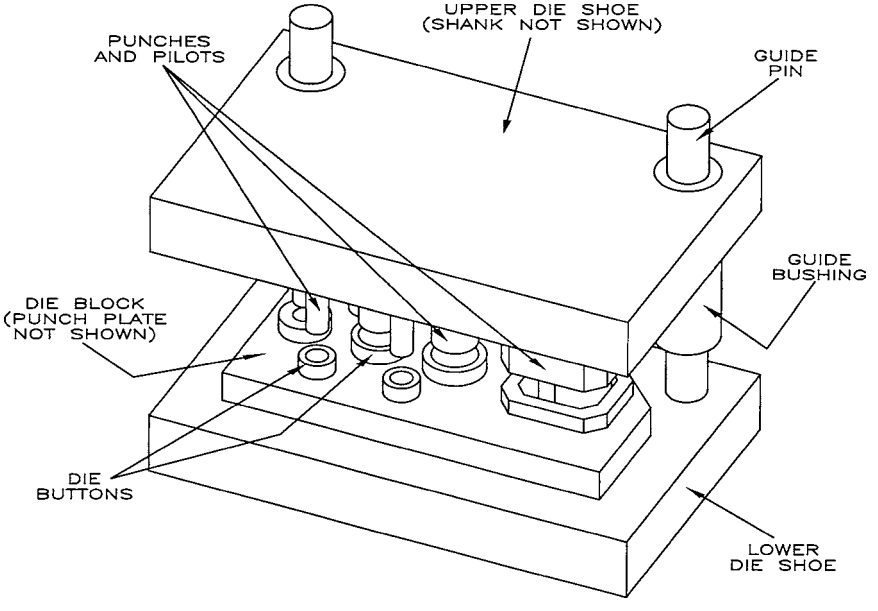

FIGURE 3-2 Progressive die.

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METAL STAMPING DIES AND THEIR FUNCTION

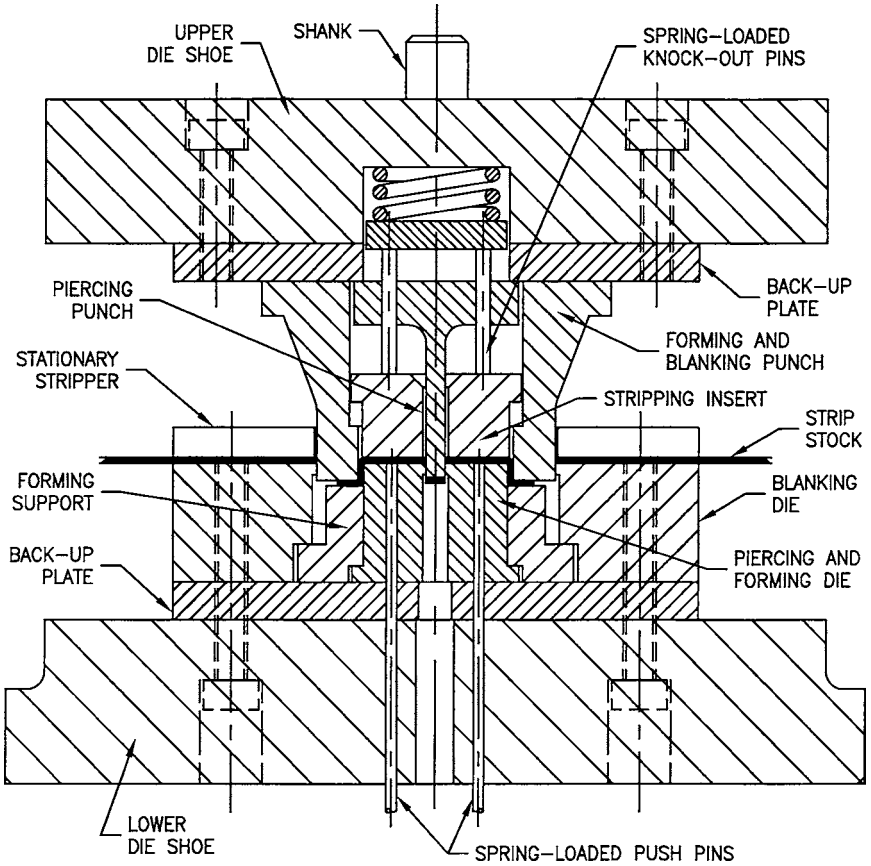

FIGURE 3-3 Compound die, producing a pierced cup.

The cross-section of a typical die set is shown in Fig. 3-3. Here the knock out pins are going through the head of the punch, their stripping pressure being provided by a spring. The pins force the pressure pad or stripping insert out against the material, so that the blank is held down when the punch moves upward. Their pressure increases with the descent of the die. The die contains a similar set of pins, here called *push pins*. These lift up the cup off the die face after forming.

The stripper is stationary, and it prevents the remainder of the strip from moving up on opening of the die, along with the movement of forming/blanking punch. This punch cuts the blank out of the strip with its outer diameter, forming it afterward with its face area and inner diameter's edge, finally bottoming on a forming support.

3-1-1 Die Shoe Types

The upper and lower die shoe, along with guide posts, can be purchased at various sizes. The two basic types of these die sets are:

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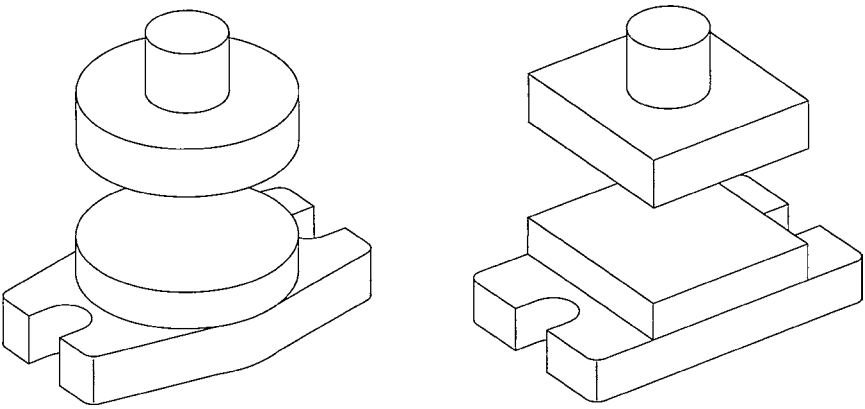

FIGURE 3-4 Open die sets.

- Open die set, (Fig. 3-4) which is used for manufacture of simple parts in small quantities or where no close tolerances are required. It is the most inexpensive die set, but since the guide posts are not there to secure the alignment of the two halves, setting up of these tools in press is often problematic.
- Pillar die set (Fig. 3-5) comes in a wide range of shapes, sizes, and combinations. The pillars, or guide posts, can be located in various places. Back post die sets have two guide posts located in the back, two post die sets have the posts placed either diagonally or opposite each other. Four post die sets contain one guide post in each corner.

Guide posts provide a perfect alignment between the two halves of the die. They keep the punches and die buttons in a fixed location against each other, which protects their cutting edges from damage. The press-mounting demands are decreased as the die alignment is already built-in. The storage and transportation of the die places no strain on its elements, thus guarding their working surfaces and extending the die life.

The vast majority of die work is done with die sets that have two guide posts. But where greater accuracy is required or for heavy gauge strips or large size dies, four post die sets are a better choice.

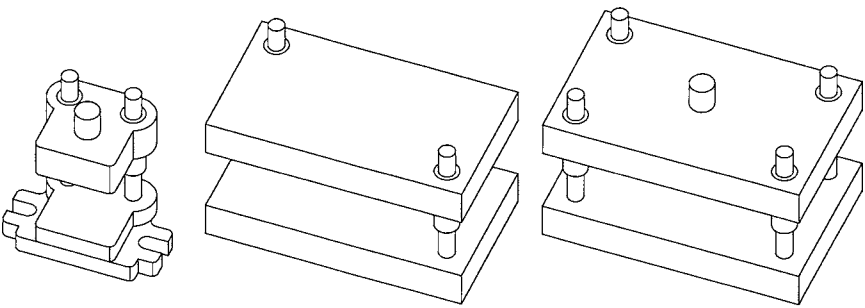

FIGURE 3-5 Pillar die sets.

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METAL STAMPING DIES AND THEIR FUNCTION

3-1-2 Die Set Selection Guidelines

Die sets are manufactured in three accuracy groups:

1. *Commercial die sets*, with tolerances between guide posts and bushings from 0.0004 to 0.0008 in. (0.010 to 0.020 mm). Commercial die sets should be used for dies where no piercing, blanking, or any other cutting is performed, such as forming and bending dies.
2. *Precision die sets*, where the alignment between guide posts and bushings is further perfected by precision grinding of the bushing's inner opening, as well as its outer diameter, which is press-fitted into the die shoe. The alignment of these dies is excellent, and they should be specified for cutting, piercing, blanking, and perforating dies.
3. *Ball-bearing die sets* with ball-bearing arrangement in place of plain sleeve bushings. These die sets are very tight-fitting, and they completely eliminate the possible development of thrust stresses or so-called side-play. Die sets with ball bearings are recommended for materials over 0.015 in. (0.38 mm) thick; pin sets may be used for all sheet stock under 0.015 in. (0.38 mm) in thickness.

Die shoes are manufactured from various types of material, the choice of which depends on the demands for strength. The three choices of die-shoe materials are:

1. *Semi-steel die sets*, are actually made of cast iron, with some 7 percent of steel added. Semi-steel die sets cannot be used where large openings in the lower shoe are required, since they may crack under the press-induced operational stresses on the die.
2. *All-steel die sets* are used where large openings such as those for blank removal or tooling insertion are to be provided in the shoe, or where milling of pockets is involved. Since all die shoes come from their respective manufacturers stress-relieved, no extensive milling or cutting should be attempted afterward. If such openings or channels are necessary, their drawings should be supplied along with the die set order and the die shoe manufacturer should produce them in the blocks, stress-relieving then after such operations.

   Where a die set is not stress-relieved after cutting or milling, all stresses remaining within the material would be slowly released over the time, which will ruin the consistency of the die material and eventually ruin the die with all its components.
3. *Combination die sets* with an all-steel lower shoe (die holder) and semi-steel upper shoe (punch holder).

3-1-3 Die Set Mounting

Each die set comes equipped with a mounting arrangement. In many cases this consists of a shank (see Fig. 3-3), which is either welded or screwed to the upper die shoe. With semi-steel die sets the shank is cast along with the upper shoe and machined to size afterward. The size of the shank depends on the mounting dimensions of the press the die is intended for.

With die sets of greater weight, an additional holding provision is added in the form of socket cap screws inserted through the upper die shoe to the underside of the ram.

The upper half of the die shoe is always firmly mounted to the ram of the press while the lower half is attached to the press bed. However, the attachment of the die's lower half should never be firm and tight, as the die needs some minute space to move around, if necessary. The bottom attachment should therefore be snug, but never rigid.

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Many may question the die's "moving around," but there are indeed many instances when the die arrangement changes. This may be due to the variation in temperature, introduction of stresses during the production cycle, relaxation of such stresses at the end, to name a few. These changes may produce some minimal variations in size or location, often almost microscopic, but as with everything else they do add up and if a die would be firmly tightened at both ends, damage to the tool may result.

3-1-4 Die-Shoe Size and the Forces Affecting its Choice

Dimensions of the blocks as well as dimensions of the whole die are governed not only by the size of the press opening, but by the requirements for strength and stability of the tool as well. Ideally, the overall size of the die should accommodate for the distribution of the utilized press force in such a way that the center of all piercing, bending, forming, embossing, and other operations is located under the shank in the center of the tool. This does not mean we should measure the distance off the center of each punch to the center of the tool. Rather, the amount of force required to do the particular operation has to be accounted for and the center of all such operations be established (see Sec. 6-6 for methods of calculation).

For example, where a lot of punching activity is concentrated at the beginning of the die and just a simple cutoff opposite from it, balancing such operations in one direction only, or x, will not provide us with a correct tooling center. Rather, the press-force distribution must be evaluated in both directions, x and y to come up with the correctly placed center of forces.

The approximate size of the die shoe with regard to the press force is given in Table 3-1. These values can be recalculated for any situation by adding the appropriate values to the formula below.

$$d = \frac{P(L^3)}{48\,EI} \tag{3-1}$$

where d = deflection, predetermined (i.e., 0.003 in. or 0.08 mm)
p = press force
L = distance between the supports (refer to the Table 3-1)
E = modulus of elasticity, 30×10^6 for steel
I = moment of inertia of the cross-section subjected to bending. The cross-section is a rectangle, $b \times d$

where b is the width of the block and d is the depth of the block.

Naturally, this formula can be used for calculation of various die blocks' sizes as well.

3-1-4-1 Maximum Stress on the Die. Along with deflection, the maximum stress on the tool is of crucial importance and it must always remain within the given limits. The maximum stress can be calculated using the formula below:

$$S_{\max} = \frac{PL}{4Z} \tag{3-2}$$

where $S_{\max}$ = maximum stress
Z = section modulus of the cross-section of the block (i.e., beam). It can be calculated by taking the moment of inertia (I), and dividing it by the distance between the neutral axes to the extreme fiber.

A tolerable compressive stress level for different materials is listed in Table 3-2.

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METAL STAMPING DIES AND THEIR FUNCTION

TABLE 3-1 Thicknesses of Steel, Lower Die Shoes Having a Centrally Applied Load

		Distance between parallels, in.						
Load, tons	Shoe width, in.	5	10	15	20	25	30	40
10	10	1.30	2.60	3.80				
20	10	1.60	3.20	4.80				
30	10	1.80	3.70	5.50				
40	10	2.00	4.10	6.10				
50	20	1.70	3.50	5.20	6.90			
60	20	1.80	3.70	5.50	7.40			
70	20	1.90	3.90	5.80	7.80			
80	20	2.00	4.10	6.10	8.10			
90	30	1.80	3.70	5.50	7.40	9.20	11.00	
100	30	1.90	3.80	5.70	7.60	9.50	11.50	
150	30	2.20	4.40	6.50	8.70	10.90	13.10	
200	40	2.20	4.40	6.50	8.70	10.90	13.10	17.50
250	40	2.40	4.60	7.00	9.40	11.80	14.10	18.80
300	40	2.50	5.00	7.50	10.00	12.50	15.00	20.00
350	50	2.40	4.80	7.40	9.80	12.20	14.70	19.60
400	50	2.60	5.10	7.70	10.20	12.80	15.30	20.40
450	50	2.70	5.30	8.00	10.60	13.30	16.00	21.30
500	50	2.80	5.50	8.30	11.00	13.80	16.50	22.00

Note: 1. Calculations are based on a deflection of 0.001 in.

2. To obtain thicknesses for cast-iron shoes, multiply table values by 1.15.

3. For an allowable deflection of 0.002 in. (0.05 mm), multiply table values by 0.785. For 0.005-in. (0.13 mm) deflection, multiply by 0.580.

4. If parallels are not used beneath the lower shoe, the value may be the combined thickness of the shoe and bolster.

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3-1-4-2 Thrust Force. Thrust force is a multidirectional force against the die block, which originates in almost every die operation. This force can be calculated using the formula 2-16. Thrust forces are generated by any forming and drawing operation, and to a degree by ordinary cutting as well. Certain processes, such as unguided wipe forming, can add a considerable amount of this side-acting force. Angular contact areas in cams are also well known sources of thrust force as well as nonsymmetrical drawing and forming. Analogically, a round, perfectly centered blanking station generates a minimum of thrust force.

But not only die components should be considered the thrust forces' origin; a faulty alignment of the press ram with the press bed can, in itself, affect the die with huge amounts of thrust force.

Some thrust forces are certainly negated by the guiding system of the die (see Sec. 3-1-5), but where some intense operations are being performed, those sections should be guided separately.

TABLE 3-2 Maximum Compressive Stress on the Material

Low carbon steel	2.5 ton/in.^{2}
Steel of up to 300 HB	3.5 ton/in.^{2}
Steels 44 HRc and harder	5 ton/in.^{2}
H13 steels, heat treated to 54 HRc	5 ton/in.^{2}

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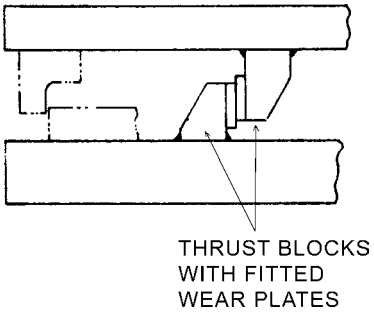

FIGURE 3-6 Complementing die guidance system. (*From: Practical Aids For Experienced Die Engineer, 1980. Reprinted with permission From Arntech Publishers, Jeffersontown, KY.*)

3-1-5 Die-Guiding Arrangement

The guidance system of a die usually consists of locating pins, heels, locating blocks, or cam-simulating, interlocking arrangements. Where friction is expected, wear plates can be added as shown in Fig. 3-6.

Guide pins, where used, should be of large diameters and as short as possible. The pins should be fully contained in the opposite opening at the time the thrust forces are being generated by a particular operation. The same applies to heels: Their contact areas must be fully engaged and totally utilized at the time of thrust-generating action.

Overall, the die is guided and protected against a movement, shift, or thrust, by its own guiding system. As already mentioned, such guiding arrangement often consists of guide bushings firmly attached to the bottom die shoe into which a guide pin trapped in the upper die shoe slides. Of course, there are many variations to this type of arrangement.

Basically, guiding arrangements are of two kinds: the first is that where the pin slides over a ball-bearing-lined guide bushing (Fig. 3-7*a*); in the second, the pin is sliding in a plain-surface-bearing (Fig. 3-7*b*).

Guide pins, also called *guide posts*, are precision ground pins, made of hardened, centerless-ground steel for commercial die sets, and of hardened, centered-ground steel for

FIGURE 3-7 Ball bearing and plain bushing die set. (*Reprinted with permission from Danly IEM, Cleveland, OH.*)

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METAL STAMPING DIES AND THEIR FUNCTION

precision die sets. To reduce friction and to increase guide posts' resistance to wear, the posts used in precision die sets are hard chromium plated.

Guide posts' length should be sufficient so that they never come out of their bushings during the press operation. This requirement is essential for the safety of work and alignment as well. The pins should always be ordered ¼ in. (6.5 mm) shorter than the shut height of the die. The *shut height* of the die is the distance between the outer surfaces of the upper and lower die shoe with the die in its lowest position. This dimension does not include the length of the punch holder (i.e., shank).

The ¼ in. (6.5 mm) distance off the die shut height, which is the minimal working height of the die is an adequate grinding allowance. It also provides for clearance between the two halves of the die during its operation.

Some manufacturers supply their die sets with one guide post longer than the other one(s), the usual difference being ½ in. (12.7 mm). It is expected that the upper die shoe first enters the longer guide post's bushing, aligns itself around it, and only then engages the additional, shorter guide post(s) in their receptacles.

Removable guide posts are usually located on a taper pin, which is attached to the lower die shoe with a screw.

The *die bushings* can be headless (i.e., a plain sleeve), or shoulder bushings. The latter type is recommended for all cutting, piercing, and blanking dies. Like the guide posts, bushings are press-fitted into the die shoe (see Fig. 3-8). Where no ball bearings are used, the smooth inner surface of the bushing is crisscrossed with helical grooves, which provide lubrication during the die operation. Some bushings, made of powdered alloy steel, are self-lubricating, since the lubricant is already entrapped in their pores. Such lubrication usually lasts the entire life of the bushing.

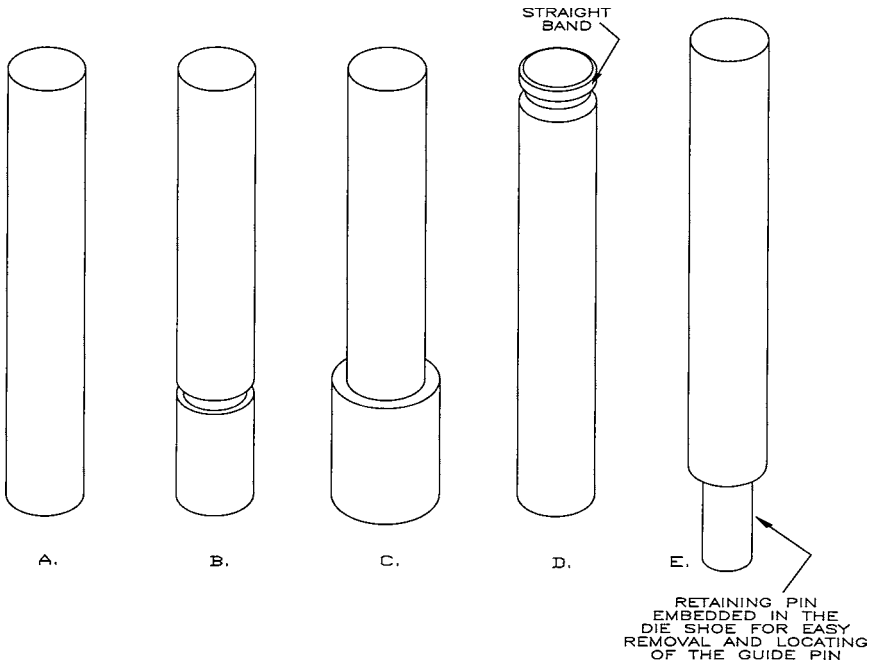

FIGURE 3-8 Types of guide posts.

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The contact surfaces between the guide post and the guide bushing are machined into such a fine finish that they tend to stick together. This problem occurs especially at the beginning when the die is assembled together just before the bushing is fully engaged by the guide post. To alleviate this problem, the ends of these guide posts should be altered as shown in Fig. 3-6*d*. The narrow band enters the bushing first, and because its width allows for rocking of the part, no sticking will occur. The slanted surface guides the post farther into the bushing.

3-1-6 Set Blocks and Stop Blocks

Heightwise, the die is protected from damaging itself by so-called *set blocks*, or timing blocks, or by rather crude stop blocks. These are pieces of steel added in between the die shoes in at least two locations, which, by their bulk, prevent the two halves of the die from smashing into each other.

The height of the set blocks can be determined by observing the die components during the absolute minimum shut height of the tool:

- Pierce punches must be entered in their dies and their face surfaces must be in the expected depths.
- Pilots must be engaged as much as they should be.
- All coining punches must be at the maximum of their penetration.
- All forming must be completed.
- Cam movements must be at the maximum limit of their travel.

At such arrangements, the set blocks must have a 0.010 in. (0.25 mm) gap between their top surface and the upper die shoe as shown in Fig. 3-9. Sometimes, a small block of lead is placed on the standard 0.050 in. (1.3 mm) high step in the set block (see Fig. 3-9*b*) and is carefully coined by sliding down the ram until its height becomes 0.060 in. (1.5 mm).

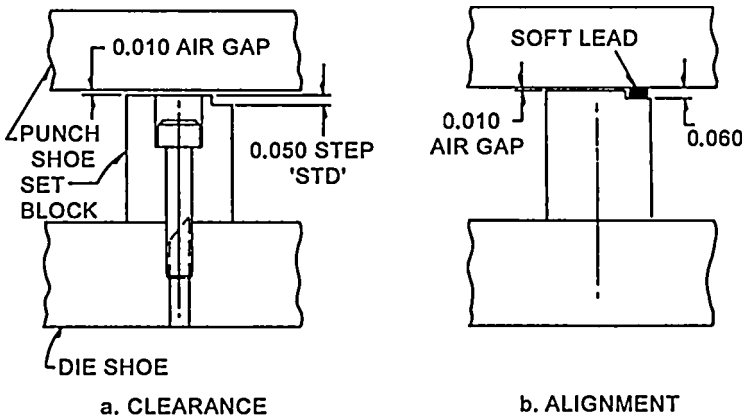

FIGURE 3-9 Set blocks' clearance and alignment. (*From: Practical Aids For Experienced Die Engineer, 1980. Reprinted with permission From Arntech Publishers, Jeffersontown, KY.*)

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METAL STAMPING DIES AND THEIR FUNCTION

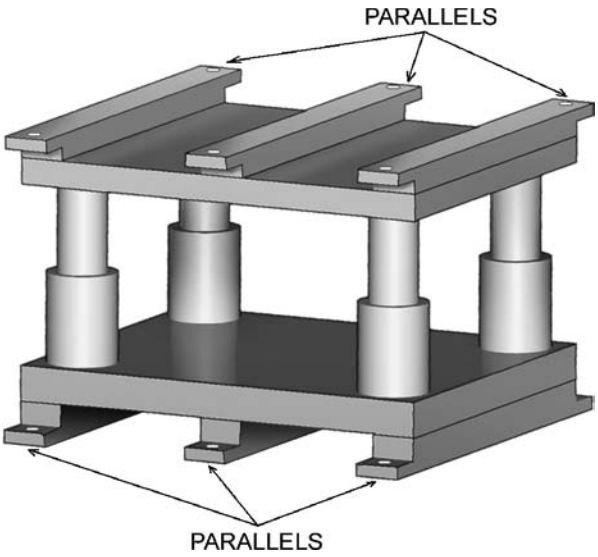

FIGURE 3-10 Parallels.

3-1-7 Parallels

Under the force of the press, an excessive deflection can produce many detrimental changes in the material of the die and subsequently in its components. Not only does this deflection need to be carefully assessed and supports placed where required, but also the die shoes themselves should be protected from accidentally succumbing to greater-than-needed forces under the ram.

Aside from set blocks or stop blocks, one additional item that further protects the die from damage are parallels (see Fig. 3-10). Parallels are steel blocks attached to the bottom and sometimes also to the top of the die, which provide a seating or mating arrangement for the die shoe. At least three or four parallels are needed for a die to provide this tool with the expected protection. Any bottoming operations, such as coining, V-die bending, or flattening, should be supported by a parallel, located in that area. The same applies to set blocks, or stop blocks—these too must be supported by the addition of parallels to their location.

The pattern of parallels' placement can get tricky where piercing and other slug producing operations are concentrated. Care must be taken so that the parallels do not obstruct the relief openings of such stations. Parallels are also important for lifting the die with a forklift truck, and their distance with regards to the size of forks should not be overlooked. A chart showing the recommended parallels' distances is shown in Table 3-1.

3-2 DIES, ACCORDING TO THEIR CONSTRUCTION

There are considerable differences in a way dies are built to function. In some, the metal strip is fed through the die, which produces the desired part in stages. Another die makes a complete part with a single hit of a single station. According to their construction and function,

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all dies can be separated into the following four groups:

- Compound dies
- Progressive dies
- Steel-rule dies
- Miscellaneous dies

3-2-1 Compound Dies

Compound dies (shown earlier in Fig. 3-1 and 3-3) produce very accurate parts, but their production rate is quite slow. These dies consist of a single station where the part is most often blanked out and either formed, embossed, pierced, or otherwise adjusted in a single stroke of the press. No progression of the strip is involved, as each stroke of the press produces a single, complete part.

Some compound dies are used just for trimming, others are specialized for blanking. There may be compound dies with interchangeable inserts, which can produce several different products just by switching between them. And there are dies used for cut off only, which, just by banking off different stops, can produce cuts of the same configuration on parts of different lengths.

Several compound dies can be involved in production of a single part, which, during the manufacturing process, is transferred as in progression from one die to another.

There are many variations of compound dies, all of them having one feature in common: with each stroke of the press, a minimum of one operation is being performed. *Combination dies* combine at least two operations during each stroke of the press. Otherwise these two types of dies are so similar in their construction and application that their names are often considered interchangeable.

Some shops, however, are making a distinction between the two types calling any cutting and forming die a combination die, while the compound die is considered only a cutting die.

3-2-2 Progressive Dies

Progressive dies (shown earlier in Fig. 3-2) are a mixture of various single dies operating as different stations and grouped into the same die shoe. These stations are positioned to follow a sequence of operations needed to produce the required part. Usually, the die sequence is arranged side by side, or horizontally. The vertical arrangement of operations is shown in Fig. 3-11. Such dies are called *tandem dies*, and are used mostly for drawing of shell types of products.

Gang dies (Fig. 3-12) or *multiple dies* are used where a large amount of simple blanks is required. The die consists of duplicate punches and dies, which cut as many blanks as there are tools during each stroke of the press.

Lamination dies are utilized where very precise and accurate work is to be done on very thin and hard material (Fig. 3-13). Most often, silicon-steel material is used, which is extremely tough. The thickness runs between 0.014 and 0.017 in. (0.35 and 0.45 mm).

The tooling to produce this type of work is not easy to manufacture. Laminations must be produced with practically no burrs, and for that reason the clearance between punches and dies is almost none. Further, these tools are usually made in sections whenever possible to allow for their quick and easy replacement.

Perforating such a hard material can soon render inadequate all common carbon steel punches and dies. Therefore, high-chrome, high-carbon steel must be used on all laminating work.

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METAL STAMPING DIES AND THEIR FUNCTION

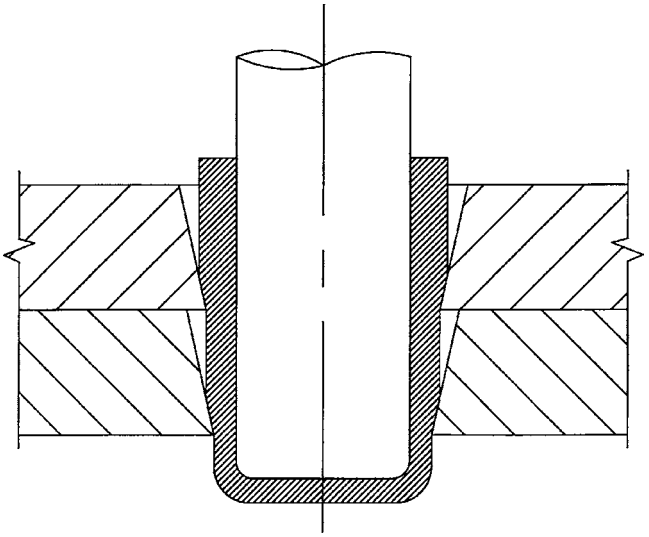

FIGURE 3-11 Tandem die.

Even though for the required level of precision, the compound die would be the appropriate production tool in laminating work, progressive dies are most often used, since they run faster and allow for stacking of parts. Often, a compound blanking station may be utilized within the progressive die. In such a case, the blanked part is forced back into the strip and carried farther to another station where it is pushed out and stacked. Such blanking is called *return blanking* as shown in Fig. 3-14.

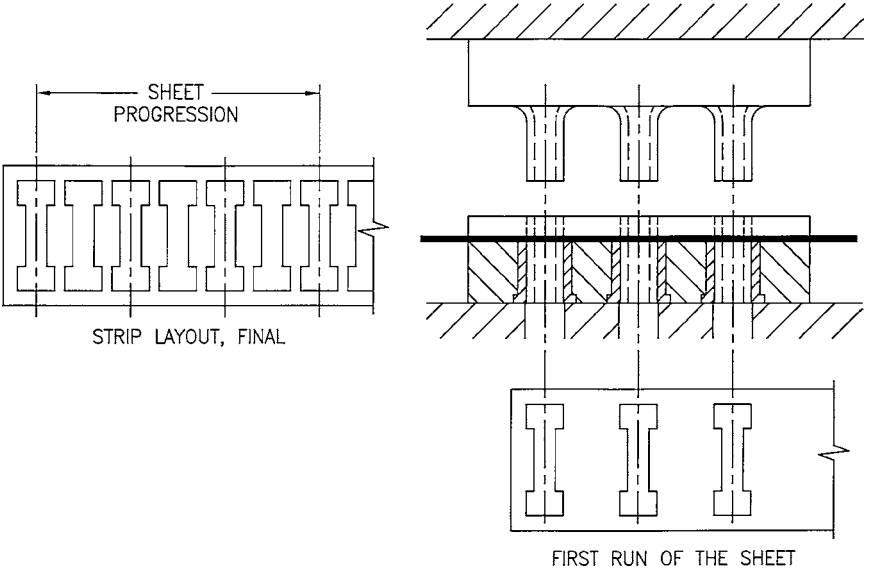

FIGURE 3-12 Gang die.

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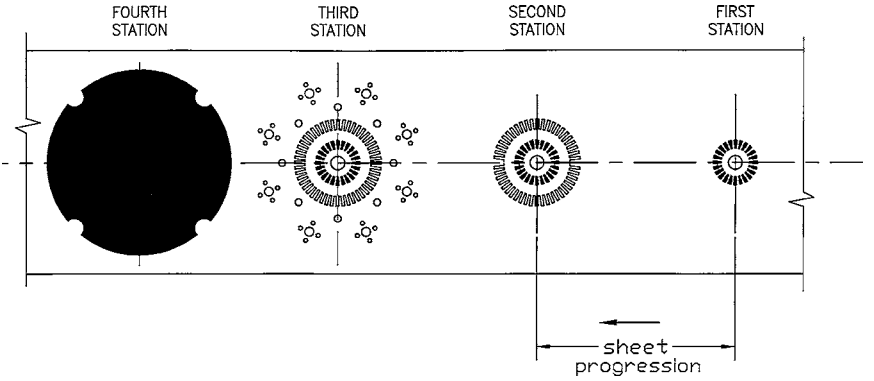

FIGURE 3-13 Piercing and blanking of laminating strip.

During the operation of such a die, the strip is fed over the bottom punch, which is surrounded by two spring-loaded stripping inserts. When the upper portion of the die slides down, the spring-loaded stripping inserts are pushed down against the force of their springs, while cutting is performed by the two upper die segments. During the cutting process, the two spring-loaded stripping inserts yield to the pressure of the die and as soon as the upper

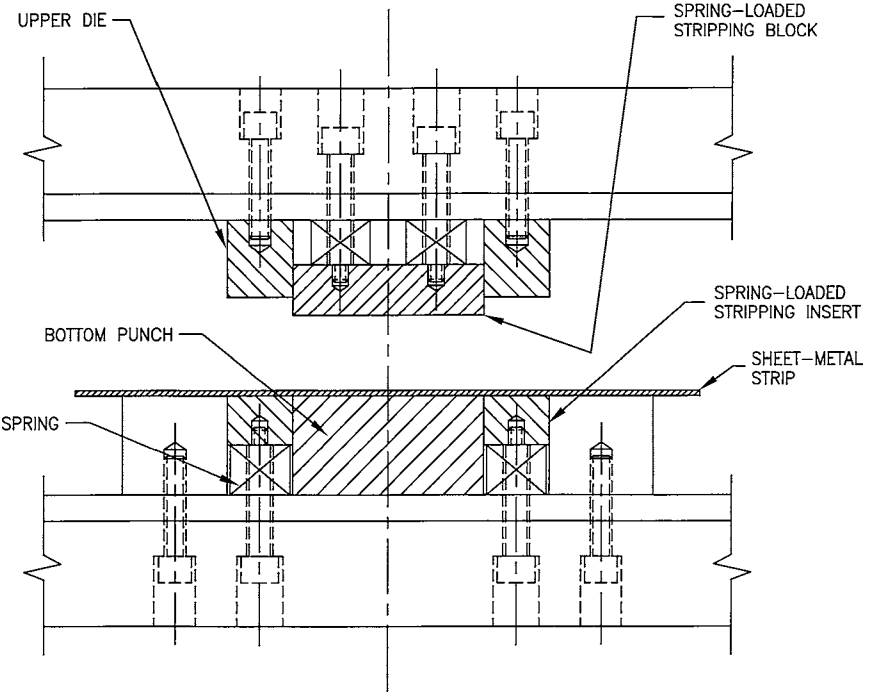

FIGURE 3-14 Return blanking.

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portion begins to recede, they push the cut pieces up, back into the strip. Owing to the force exerted by its springs, the upper stripping block holds the pressure against the sheet longer than it takes for the punch to withdraw, thus holding down the section into which the cut pieces are being forced.

3-2-3 Steel-Rule Dies

Also called metalform dies, steel-rule dies consist of a heavy strip steel which serves as the cutting edge when mounted in a standard die set. Plastic and paper cutting steel-rule dies may be mounted on a heavy plywood plate instead of die set.

The way the strip steel is attached to the block, its function is the same as that of a cutting knife. But with its thin profile it has a tendency to swell up and buckle. For that reason, the strip steel's compressive force should be twice the amount of the cut material's shear coefficient.

Steel-rule dies (Fig. 3-15) are usually equipped with neoprene or rubber strippers slightly exceeding the height of the blades. Punches and dies are standard; they may be used to pierce openings while the steel rule (Fig. 3-16) is used to cut the outline of the part. Tolerances for steel blades and their mating die sections are the same as those for regular punches and dies. The thickness of the blade is given in Table 3-3.

Of course, to get the proper material for the cutting rule is of essence. After all, in many instances the whole cutting section of a steel-rule die may consist of a blade, such as the one shown in Fig. 3-16, shaped into the desired outline and retained in some fairly soft material such as plywood, plastics, and others (see Fig. 3-17). Recent research into the cutting blades' material shows that an edge-hardened material with a softer, durable inner core, shaped to create a cutting edge can outperform many other steels.

Steel-rule dies may perform blanking, trimming, piercing, forming, embossing, and extruding operations. They are often utilized for cutting papers, fibers, card stock, rubber, felt, leather, and similar soft materials. Major areas of interest for their applications in metal-working are: limited quantities of parts, short lead times, large shapes, and tolerances above ±0.005 in. (±0.13 mm).

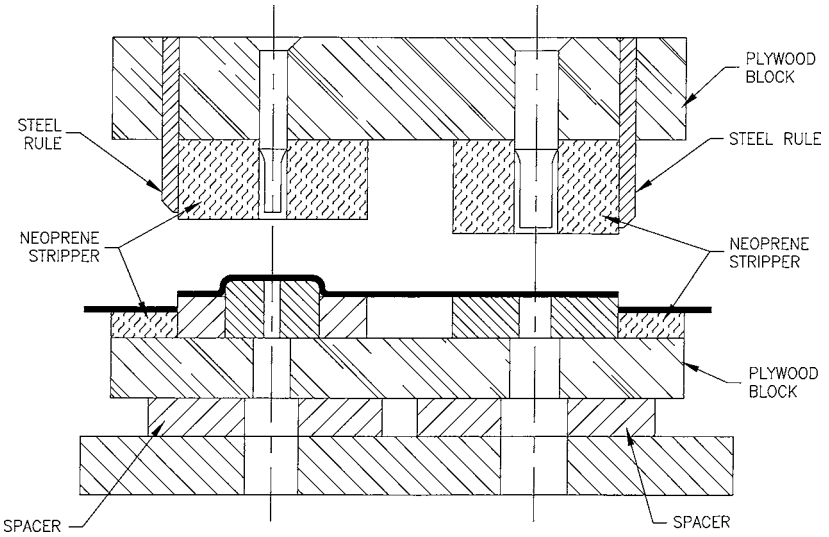

FIGURE 3-15 Steel rule die.

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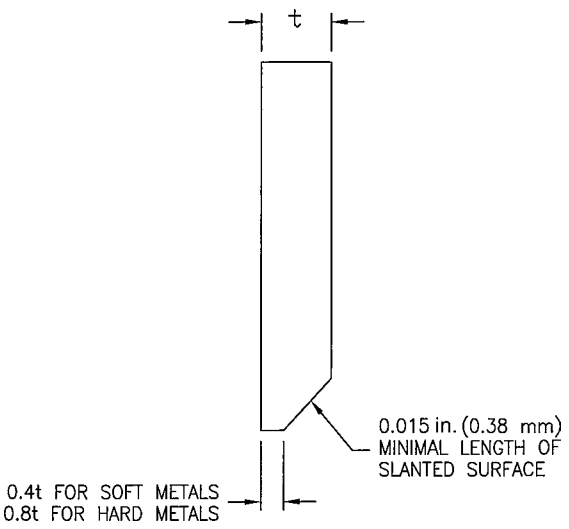

FIGURE 3-16 Steel rule.

3-2-4 Sectional and Modular Dies

Modular and sectional dies are used where the quantities of parts to be produced do not justify building a hard tool or where repeated sequences of moderate-run parts are being produced. When making a decision whether modular or hard tooling is to be used we must not only look into the suitability of each category for given production requirements, but we must also evaluate the cost and frequency of setup changes with their subsequent influence on the wear and tear of punches, dies, dowel pins, and their openings, and on all other segments of the die that will constantly be inserted, removed, and reinserted. In some modular dies, especially in those that were already designed and produced as modular components of a temporary die set, the hindrance of the tooling deterioration can often be reduced to a minimum.

TABLE 3-3 Recommended Steel Rule Thicknesses by Points for Various Materials*

Material thickness		Material						
in.	mm	Aluminum, soft	Brass ½ hard	Aluminum, 2024-T	Aluminum, 7075-T	Steel, mild	Steel, 4130	Stainless steel, 302
0.010	0.25	3	4	4	4	4	4	4
0.031	0.78	4	4	4	4	4	4	4
0.062	1.57	4	4	4	4	4	4	6
0.078	1.98	4	4	4	4	4	6	6
0.093	2.36	4	4	6	6	6	6	6
0.125	3.175	6	6	6	6	6	8	8
0.150	3.81	6	6	8	8	8	8	

*One point equals approximately 0.014 in. [0.35 mm]

Source: Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from The McGraw-Hill Companies.

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METAL STAMPING DIES AND THEIR FUNCTION

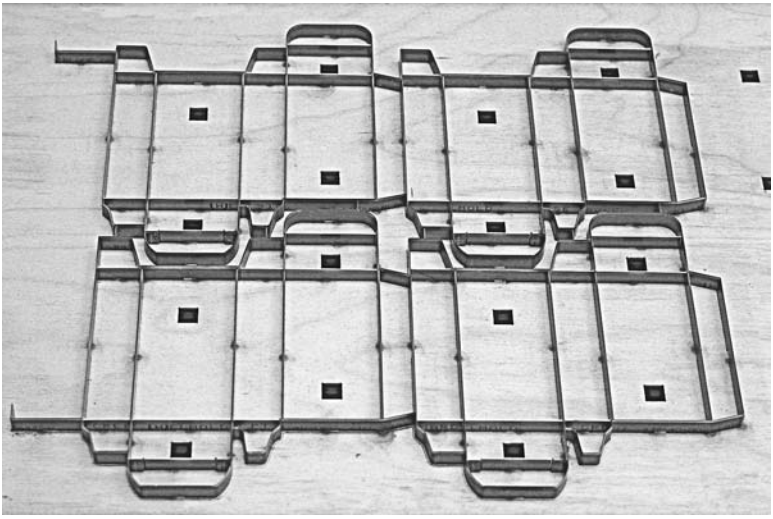

FIGURE 3-17 Sample of a steel rule die. (*Printed with permission from Lasercam Co., Ridgefield, NJ.*)

An ideal candidate for temporary tooling is such a die, where just by pulling few punches out or by adding few new ones, a different part will be produced. But even there the process of frequent removing and inserting of blocks for punch removal, addition, or exchange can wear out the press-fit of that section and render the whole tool useless much sooner than expected. If such a scenario exists, perhaps making these removable punches accessible already through the die shoe, so that the whole die does not have to be dismantled each time a change is needed, may be of help.

But even there, the wear and tear of the punches and dies and their openings in the blocks may not be appreciated few months down the road.

Within a group of modular and sectional tooling, we presently recognize three types:

- Sectional dies with interchangeable punches
- Dies with interchangeable blocks
- Modular dies

3-2-4-1 Sectional Dies. Dies consisting of various sections are very common in die design. Most of progressive dies are actually built as sectional dies with their sections or stations, assembled together in a common die shoe. This way we can have the first piercing section, the second piercing section, embossing section, bending section, cutoff section, and other sections. Many times, every station of a progressive die can be classified and also used as a self-contained unit.

Sections of blocks are relatively easy to maintain. If a punch has to be removed, we do not have to take the whole die apart; dismantling a single block will suffice. Any repair, replacement, or sharpening is simplified, and smaller changes to the die are easier.

Another way of designing a die with interchangeable components is to use retracting punches. This means where a punch has to be removed and another punch has to be added in its stead, retracting the first tool while allowing the second punch to pierce is often a way to handle the situation.

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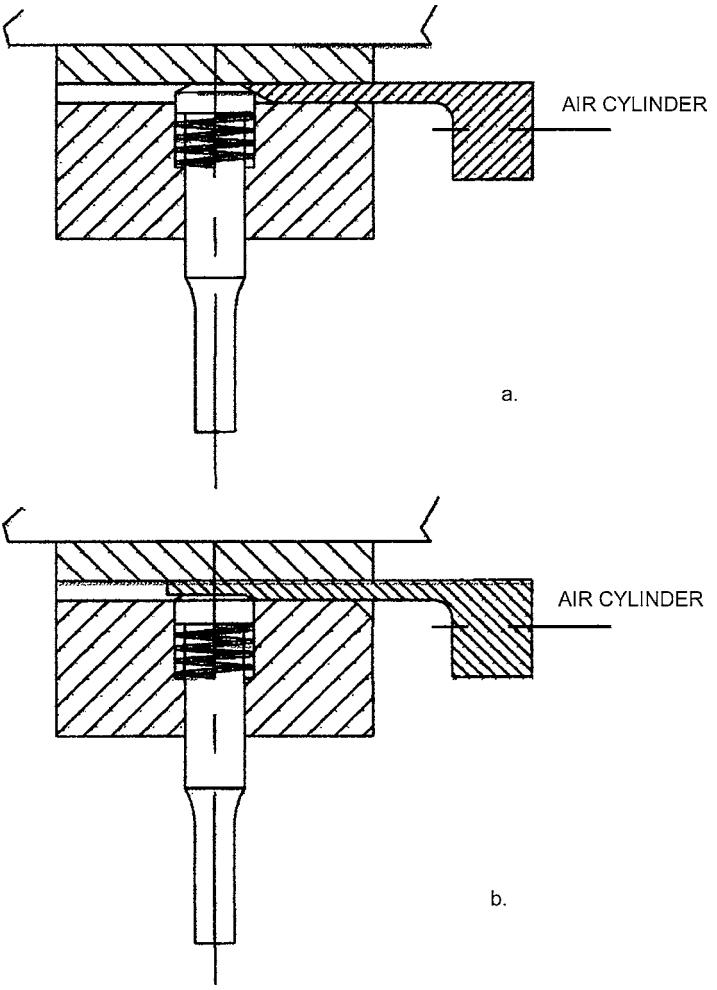

FIGURE 3-18 Retracting of a punch. (*From: MetalForming Magazine®, July 2000, by Larry Crainich. Reprinted with permission from PMA Services Inc., Independence, OH.*)

Punches can be retracted and reinserted not only by hammering them in or out. There are additional methods which allow for such change without taking the die out of the press. Shown in Fig. 3-18, a wedge is being forced between the head of the spring-loaded punch and a backup plate. When fully inserted, this wedge will bring the punch down far enough to pierce an opening. Withdrawal of the wedge will force the punch to snap back, as pushed against the back up plate by the spring force. At such a position, the tool is already too far up to have any effect on the material.

The movement of the wedge can be accomplished by any mechanical means. In production, air cylinders can be utilized with their movements activated by a microswitch. Sometimes, programmable logic controller (PLC) can be programmed to automatically implement the change after certain number of parts have already been produced.

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METAL STAMPING DIES AND THEIR FUNCTION

Another category of sectional dies comprises of tooling that is used for experimental work. Often, a difficult operation or a combination of various tasks may require the tooling to be groomed to the correct size on the basis of actual tests. In such a case, tooling can be designed and produced slightly oversized, or slightly different in other parameters and machined or ground to correct sizes after each altered shape has been tested in the press.

Two samples of sectional dies are illustrated in Fig. 3-19. Notice the uneven location of screws and dowels. In die work it is a common practice to prevent any variation from the proper installation of the block. The mounting openings are distributed to fit only that half of the die block they should fit; the other half of the block will not be possible to attach.

When designing a sectional die, the possibility of whole blocks or their segments being exchanged for differently shaped portions is of essence. We can use a die shoe into which a whole group of die blocks and punch plates provided with the same mounting holes fit. Each of these blocks may produce a slightly different part, sometimes just by changing their cutting inserts. For example, only the center portion of the irregular block pictured in Fig. 3-19 may need to be replaced for the next run.

Unfortunately, these dies lose their accuracy with time, as their supposedly press-fit dowel pins become looser and looser in their retaining openings, or even scarred from too-frequent manipulations. Of course, mounting holes can be opened up and a larger set of dowels utilized, which will improve the accuracy somewhat. However, we should not forget that when enlarging dowel-pin openings or any other openings, we must, similarly, open the same openings in all other blocks this arrangement is using. This can become still more complicated by the fact that not all shops have the capacity for accurately picking the hole center and that a slight shift in its location may be detrimental to the whole tool.

When moving the blocks in and out of the die, we must bear in mind that once we start tampering with the exact locations of die components, we are additionally inviting problems with their alignment. Each such manipulation may throw the blocks out of their exact position in either direction and a whole load of shims may be needed to bring the die back to operation.

Some shops resort to replacing temporary dies by producing the parts in numerically controlled (NC) machines. True, NC turret press can produce many of these parts with ease. Yet, the setup drawbacks remain as it is equally difficult to locate the punches and proper clearance dies, and assemble them into their tool holders. The availability of the NC machine has to be evaluated at the same time, for to use it where short-run parts will impair some long-running arrangements, or where the new tooling will not fit in between the existing setup, is not the best thing to do. Also the cost should be of essence here, for the cost of the production time for an expensive NC turret press is often much higher than the cost of an older punch press, which may be standing somewhere in the shop anyway, not utilized for any other purpose. These all elements have to be weighed before resorting to the use of any type of shortcuts, even those seemingly justified.

The use of temporary dies certainly has its place in experimental work, where it may save a lot on material, additional work, or costly operations. If a punch and die has to be

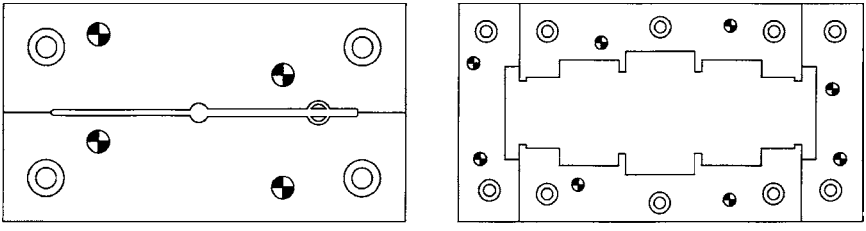

FIGURE 3-19 Die blocks made of sections.

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tried out and discarded and a new set has to be manufactured for another trial, the cost of such proceedings can be tremendous. With sectional dies, as with other temporary tooling, the parts already tried out are but altered, used again, and altered further if necessary, until the produced part meets the predetermined requirements. The same experimental tooling may later be implemented in the production die, after it has been hardened and ground to size.

3-2-4-2 Dies With Interchangeable Blocks. These die arrangements are using a similar approach, by grouping their die blocks and punch plates mounted on their support plates, into a homogeneous upper and bottom sections and inserting these whole units into a universal die shoe.

Universal die shoes are generic die sets used for different die arrangements, which are all made to fit the shoes' standard hole pattern. Some claim this method of assembly saved them a lot in die shoe costs; others claim such die shoe costs were far offset by the toolmaker's and press mechanics' costs. Such a die needs to be aligned every time it is reassembled. Sometimes, just taking the die arrangement out and placing it back into the universal die shoe can shift the sections almost invisibly, yet dangerously for the produced part. Then, a new stack of shims has to be dispersed around the assembly, the die has to be tried out, new shims inserted or replaced, and so on. Numerous setups and adjustments have often be made and all kinds of different methods of feeding of the stock, stopping the material, and lubricating the strip have to be devised. In actual and serious die work, universal die shoes are more of a hindrance than help.

3-2-4-3 Modular Dies. Modular dies (Fig. 3-20) are excellent for moderately high production volumes, where there is very little or no justification for hard tooling. Modular dies' components are standardized and reusable in different arrangements to suit various jobs. Punches and their punch holders and dies and their die holders do not have to be taken apart each time they are assembled. They can be kept as subassemblies, for fast installation in the modular system's die set. Punch and die location is provided by templates; there is a punch template and a die template, both made from heavy-gauge sheet metal with precision-machined openings, into which the punch and die arrangements fit. Powerful, permanent magnets in each punch holder keep the punch tooling perpendicular and firmly attached to the master set punch shoe. According to the manufacturer, hole-location tolerance of ±0.005 in. (0.127 mm) or better can be achieved with properly made templates.

With some types of modular dies, a reusable master die set often remains mounted in the press and the modular die components already inserted in their templates are quickly slid into position. Of course, the placement of the die parts into their templates must be performed outside the press. Accuracy of the punch plate and the die plate positioning within the die set is controlled by template support posts, which are part of the master die set. Each template assembly is secured with four clamp screws.

Bump-Style Modular Die. A so-called "bump-style" modular die (see Fig. 3-21) does not use any master die set and is not attached to the press ram. Here a series of four spring-loaded precision alignment posts insure the vertical accuracy of punch and die, as well as control the open height for loading and unloading of the workpiece. Because of their versatility, modular dies of this type can be used for production in both brakes and presses.

All segments of these dies are comparatively lightweight, easy to store, and easy to install. Punch and die templates, which actually are flat pieces of #8 gauge steel, are usually stored in vertical racks, like books in the library. Die components, punches, dies, and their retainers can be stored on shelves, or in drawers or boxes.

T-Slot Die Retaining Arrangement. This type of die-replacing arrangement (Fig. 3-22) is but another variation of modular dies. The punch and die components are arranged inside a T-slotted die set, where they are bolted in their appropriate locations with t-bolts, nuts, and washers. The advantage of being not restricted by a locating plate can be found helpful for prototype work or with many experimental die designs. True, the total versatility of

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METAL STAMPING DIES AND THEIR FUNCTION

a.

b.

FIGURE 3-20 Modular punch and die assembly and as included in the Magna® Die. (*Reprinted with permission from S.B. Whistler & Sons, Akron, NY.*)

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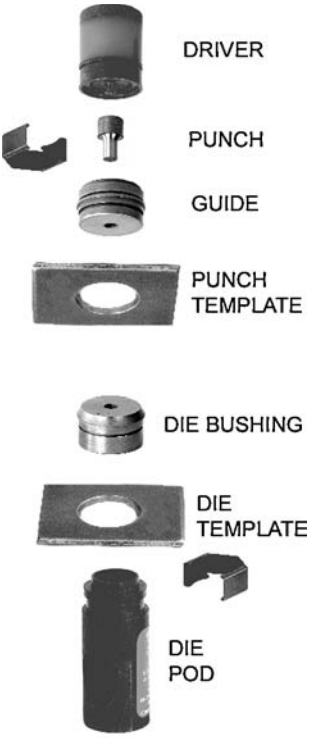
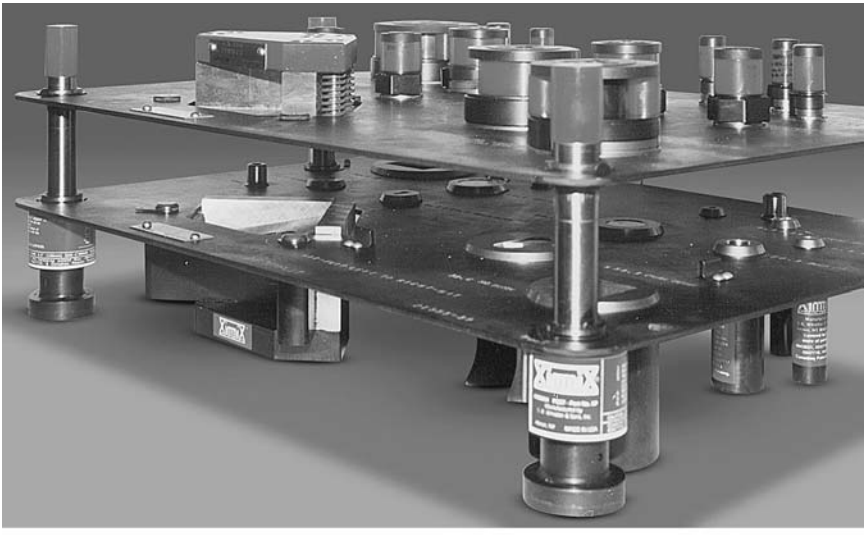


a.



b.

FIGURE 3-21 *Bump style* modular punch and die assembly and as included in the XimmiX® Die. (*Reprinted with permission from S.B. Whistler & Sons, Akron, NY.*)

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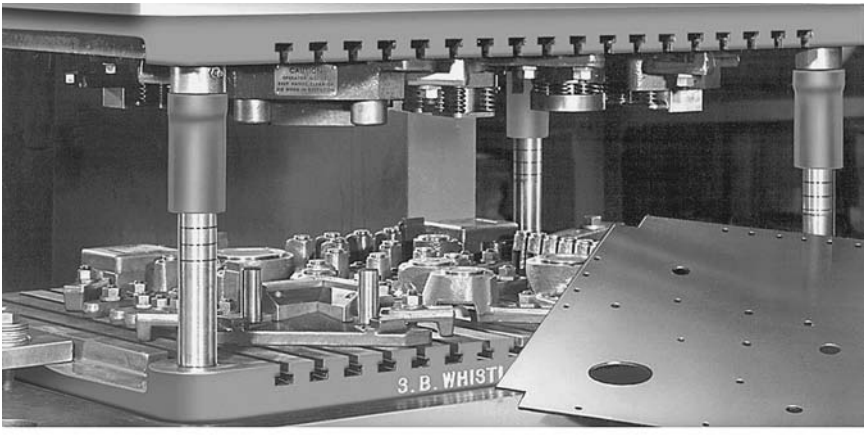
METAL STAMPING DIES AND THEIR FUNCTION

a.



b.

FIGURE 3-22 T-slot retaining arrangement and as included in the Adjustable Die. (*Reprinted with permission from S.B. Whistler & Sons, Akron, NY.*)

location may result in somewhat longer setup times. For this reason, it has to be carefully evaluated which of the scenarios is preferable for this or that job, or which of them is reusable more frequently than the other.

The die components are assembled by hand, inside the press, where the T-slot die set should already be mounted.

3-2-5 Indexing and Transfer Dies

Indexing dies (Fig. 3-23) are useful for repeated notching or perforating, where the operation is copied around a circumference of the part. An indexing die usually produces several cuts at a time, rotates (i.e., transfers) the blank, and pierces again.

This procedure can be used for parts of limited quantities where complicated tooling would be cost-prohibitive.

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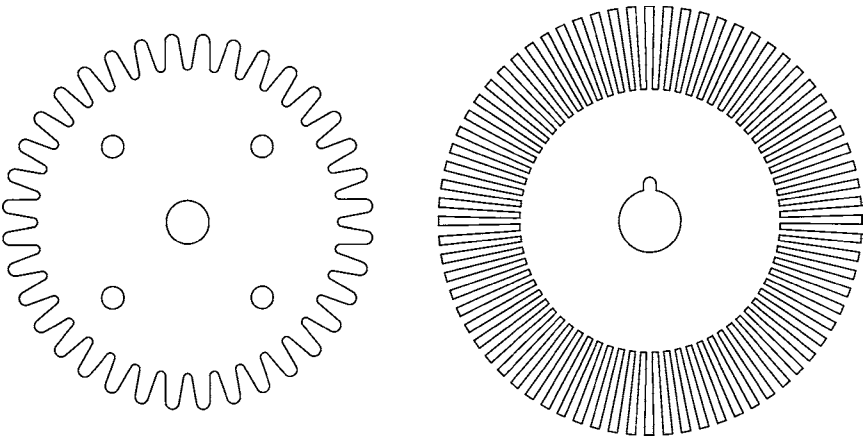

FIGURE 3-23 Indexing die samples.

Transfer dies are suited for longer runs of parts, since the die shoe, equipped with a transfer mechanism (Fig. 3-24), often cannot be easily adapted for another work.

This type of die can transfer single pieces of work from station to station, shuttling them in a linear, rather than circular fashion. The die construction itself is that of a progressive die with no strip-feeding provision. Movements of parts or movement of the material is provided by the transfer mechanism.

Sometimes the transfer device is a built-in feature of a press, in which case the press is called a *transfer press*.

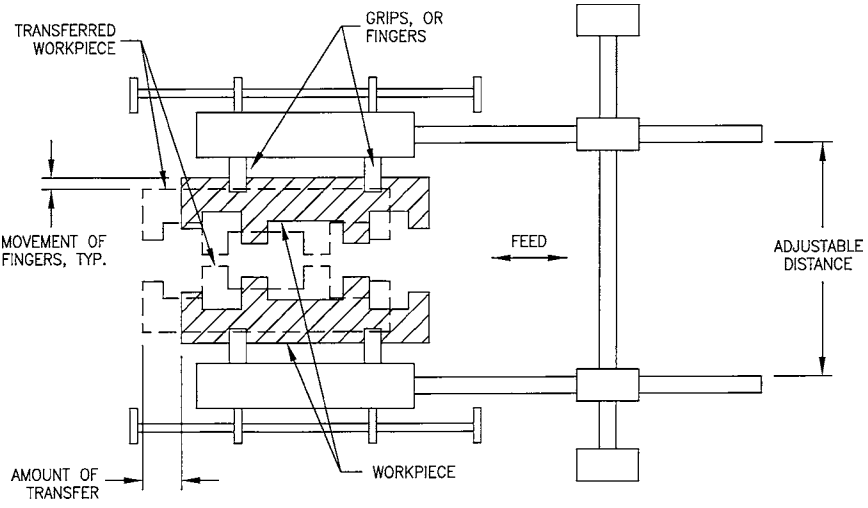

FIGURE 3-24 Transfer mechanism, simplified.

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METAL STAMPING DIES AND THEIR FUNCTION

3-3 DIES, ACCORDING TO THEIR EFFECT ON THE STRUCTURE OF MATERIAL

When evaluated for the influence a die operation exerts on the structure of sheet metal, dies can be grouped into several categories named after the operations they perform. There are blanking dies, piercing dies, and cutoff dies, which all cut the material, separating the slug from the part. Other tools are those that force the metal to flow into predetermined locations, such as tools that form the metal, stretch it, expand it, or compress it.

All the different types of dies fit loosely into five categories, where they are grouped according to the type of work they produce. These are:

- Cutting dies
- Bending and forming dies
- Drawing dies
- Compressing dies
- Miscellaneous dies

3-3-1 Cutting and Trimming Dies

These dies separate pieces of metal from the main blank or from the strip by the cutting process. They include blanking, piercing, perforating, notching, lancing, slitting (or cutoff), plunging, trimming, shaving and burnishing dies, and pinch trimming tools.

Blanking dies cut out the outline of the part in a single operation. *Piercing dies* pierce singular holes, either for pilots' engagement, or where piercing is required before or after bending, drawing, and other shape altering processes (Fig. 3-25).

Perforating dies produce a multitude of openings called perforations. This type of work is used in production of strainers, sifting devices, for shielding and ventilation of heat dissipating components, or for decorative appeal.

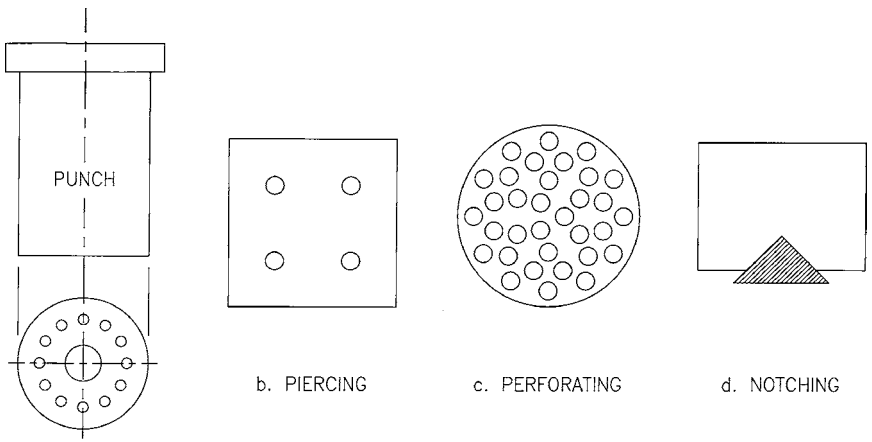

FIGURE 3-25 Cutting operations.

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Cut-off dies chop off the pieces of sheet-metal material, or that of tubing or wire from the continuous supply. Often the cut-off operation is the last of the sequence of a progressive die, in which case it cuts actual products off the strip and occasionally also cuts the scrap into manageable segments.

Notching is basically the same operation as blanking or piercing, the only difference being in the imbalance of the cut. This is because notches usually appear along the edges of parts, and if the tooling exceeds the width of the strip, that side of its shape ends up unsupported. To prevent this type of complication, notches are usually punched out first. For example, a corner fillet should be removed before the sides of the part are cut off. Heeled punches are found supportive in notching operations, along with special-shaped tooling.

Lancing (Fig. 3-26), as found in sheet-metal work, is commonly used to produce short tabs, where a single punch cuts the metal and forms it at the same time.

The forming portion of the lancing punch must have the same radius as any other bending tool. Its face area must be ground at an angle, beginning at the point where the cutting of metal first occurs. No nesting of the part is necessary in this operation.

The shape of a lance, in flat, should preferably consist of tapered edges, as shown in Fig. 3-27. Otherwise binding between the lance's edges and the wall of its tooling may occur. With tapered shape, the walls of the lance actually move away from the tooling when formed.

Slitting, or cut-off (Fig. 3-28) is another cutting operation during which the cut is only partial, and the cutout sometimes remains attached to the strip for further processing. This type of die work is used for cutting off certain areas, which will be further processed by the progressive die, or to produce so called "louvre" shapes, in which case a special-shaped forming and cutting tool is needed.

Instead of piercing of the material, sometimes a method called *plunging* is used (Fig. 3-29). The punch in this operation is called the plunger, and it does not cut through the strip, but rather it draws the metal extending its shape, and breaking through at the end of the stroke.

Extruding is a similar operation, only here the metal is prepierced and the extruding punch is used to push through the opening while forcing its circumference into extended length. With plunging, the edges are rough while extrusions have more smooth and even edges.

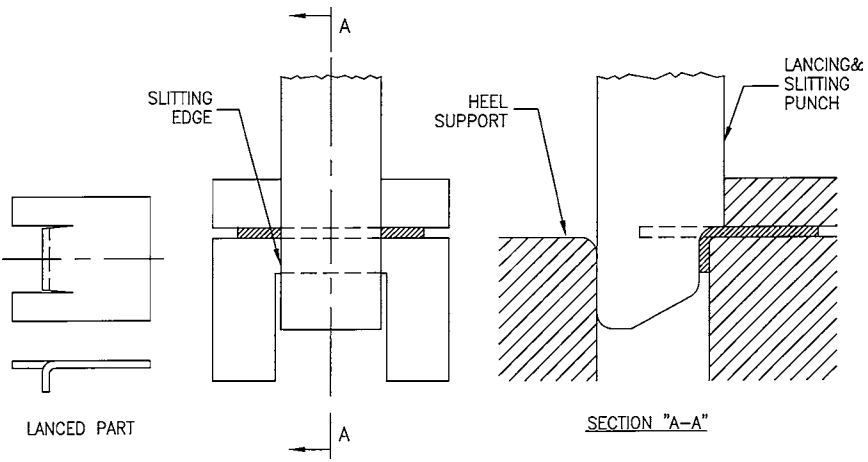

FIGURE 3-26 Lancing operation.

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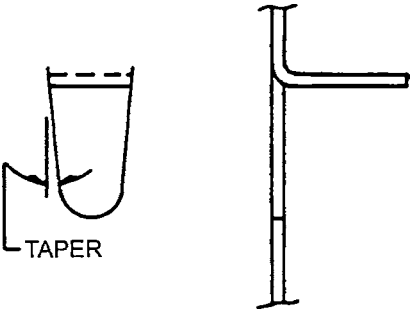

FIGURE 3-27 Detail of a lance. (*From: Practical Aids For Experienced Die Engineer, 1980. Reprinted with permission from Arntech Publishers, Jeffersontown, KY.*)

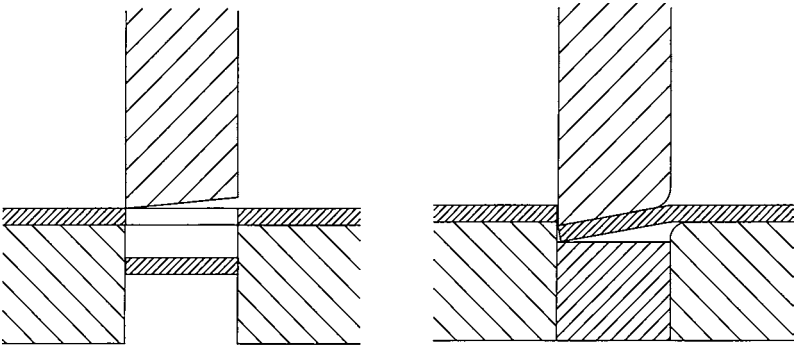

FIGURE 3-28 Cut-off and slitting operations.

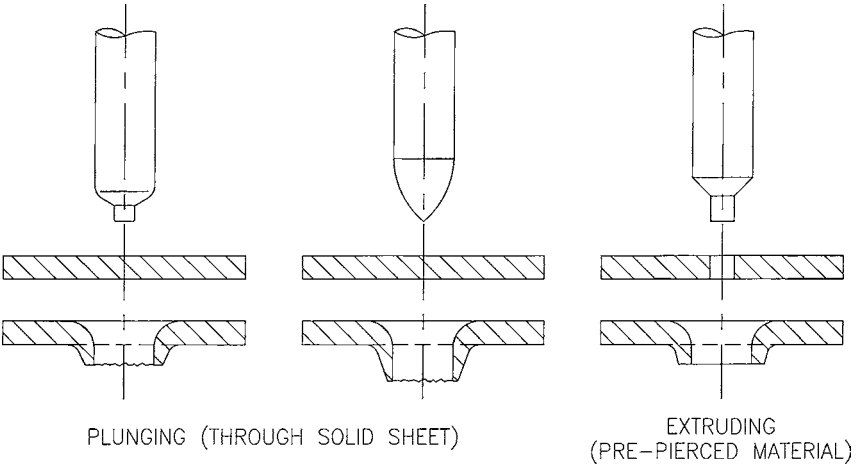

FIGURE 3-29 Plunging and extruding.

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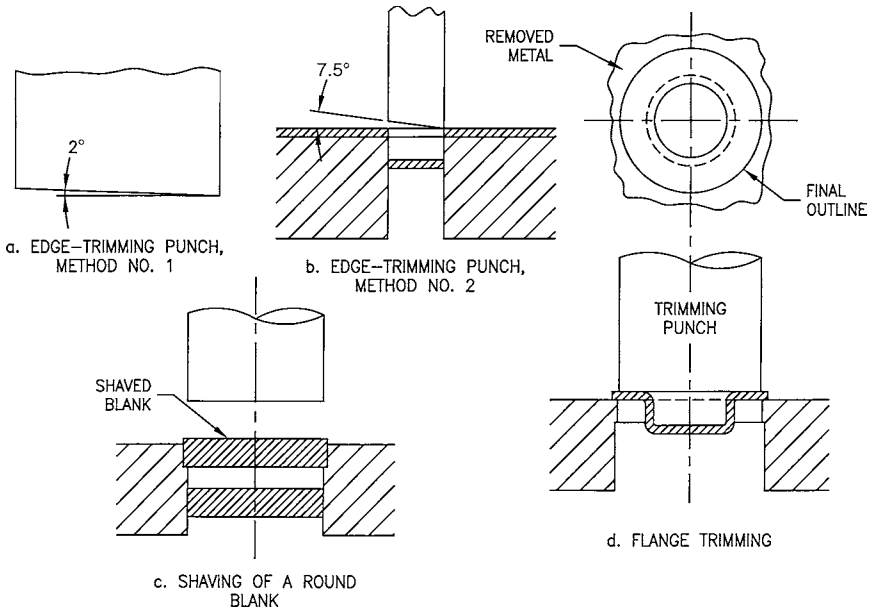

FIGURE 3-30 Trimming and shaving dies.

Trimming dies (Fig. 3-30) are used for removal of portions of material distorted during previous operations, be it forming or drawing.

Shaving dies are basically very accurate trimming tools, yet operating on a slightly different principle. They are used to remove minute amounts of material surrounding previously performed cuts. A shaving operation is used for removal of burrs and to flatten the edges of precision parts. The shaved part has a straight, clean, smooth edge, which can be held to accurate tolerances (see Tables 3-4 and 3-5).

Proper nesting is a necessity in shaving operations (see Fig. 3-30*c*). After the part is located, the shaving punch pushes it through a slightly smaller opening, forcing the material to conform to that opening's surface and size. For this reason, an accurate feeding and precise piloting of the material is important.

Where slivers of material may remain scattered over the die surface, these may have a detrimental influence on the final product's quality. They may also impair the alignment between the punch and die and sometimes even ruin the whole tool. A positive scrap removal is one of the conditions of successful shaving operation.

Shaving operation smoothes the edges, removes burrs, and is suitable for any ordinary parts. For finely finished or polished edges of precision mechanisms' components, burnishing operation should be the method of choice.

Burnishing and *sizing* (or *calibrating*) dies force the blank through a die which has no cutting clearance. The edges of the part become forcibly smooth, even, and accurate. There are two types of burnishing dies:

- Tools where the part to be burnished is forced over a radius in the die or pushed along an inclined surface of the die opening, as shown in Figs. 3-31*a, b*.
- Tools where the part is forced through the straight die opening with the punch overlapping .002 to .010 in. (0.05 to 0.25 mm) per side (Fig. 3-31*c*). This method is also used for burnishing of inner openings, as shown in Fig. 3-31*d*.

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TABLE 3-4 Shaving Alowances Per Side for Steel, Brass, and German Silver Stock

Thickness of blank		Steel Hardness 50-66 R_B		Steel Hardness 75-90 R_B		Steel Hardness 90-105 R_B		Brass and german silver	
in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Where one shave is necessary									
3/64 (0.0468)	1.19	0.0025	0.06	0.003	0.08	0.004	0.10	0.005	0.13
1/16 (0.0625)	1.59	0.003	0.08	0.004	0.10	0.005	0.13	0.006	0.15
5/64 (0.078)	1.98	0.0035	0.09	0.005	0.13	0.006–0.007	0.15–0.18	0.007	0.18
3/32 (0.0938)	2.38	0.004	0.10	0.006	0.15	0.007–0.008	0.18–0.20	0.008	0.20
7/64 (0.1094)	2.78	0.005	0.13	0.007	0.18	0.009–0.011	0.23–0.28	0.010	0.25
1/8 (0.125)	3.18	0.007	0.18	0.009	0.23	0.012–0.014	0.30–0.36	0.014	0.36
Where a second shaving operation is necessary									
3/64 (0.0468)	1.19	0.00125	0.03	0.0015	0.04	0.002	0.05	0.0025	0.06
1/16 (0.0625)	1.59	0.0015	0.04	0.002	0.05	0.0025	0.06	0.003	0.08
5/64 (0.078)	1.98	0.00175	0.045	0.0025	0.06	0.003–0.0035	0.08–0.09	0.0035	0.09
3/32 (0.0938)	2.38	0.002	0.05	0.003	0.08	0.0035–0.004	0.09–0.10	0.004	0.10
7/64 (0.1094)	2.78	0.0025	0.06	0.0035	0.09	0.0045–0.0055	0.11–0.14	0.005	0.13
1/8 (0.125)	3.18	0.0035	0.09	0.0045	0.11	0.006–0.007	0.15–0.18	0.007	0.18

Source: Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from The McGraw Hill Companies.

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TABLE 3-5 Shaving Allowances for Aluminum

Thickness of blank		First shave allowance		Final shave allowance	
in.	mm	in.	mm	in.	mm
0.03	0.8			0.004	0.10
0.05	1.3			0.006	0.15
0.06	1.5			0.007	0.18
0.08	2.0	0.007	0.18	0.003	0.08
0.10	2.5	0.008	0.20	0.004	0.10
0.125	3.2	0.010	0.25	0.005	0.13
0.175	4.4	0.013	0.33	0.007	0.18
0.25	6.4	0.020	0.51	0.010	0.25

Source: Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from The McGraw-Hill Companies.

The radius of the burnishing die shown in Fig. 3-31*a* depends on the thickness of burnished material. Usually, .010 to .062 in. (0.25 to 1.5 mm) is an adequate size. The springback amounts to 0.05 to 0.06 percent of the blank's size.

The second method, shown in Fig. 3-31*c*, is reserved for softer materials, such as aluminum alloys, brass, and bronze. The difference between the punch and die should be 0.004 to 0.020 in. (0.10 to 0.50 mm) per diameter.

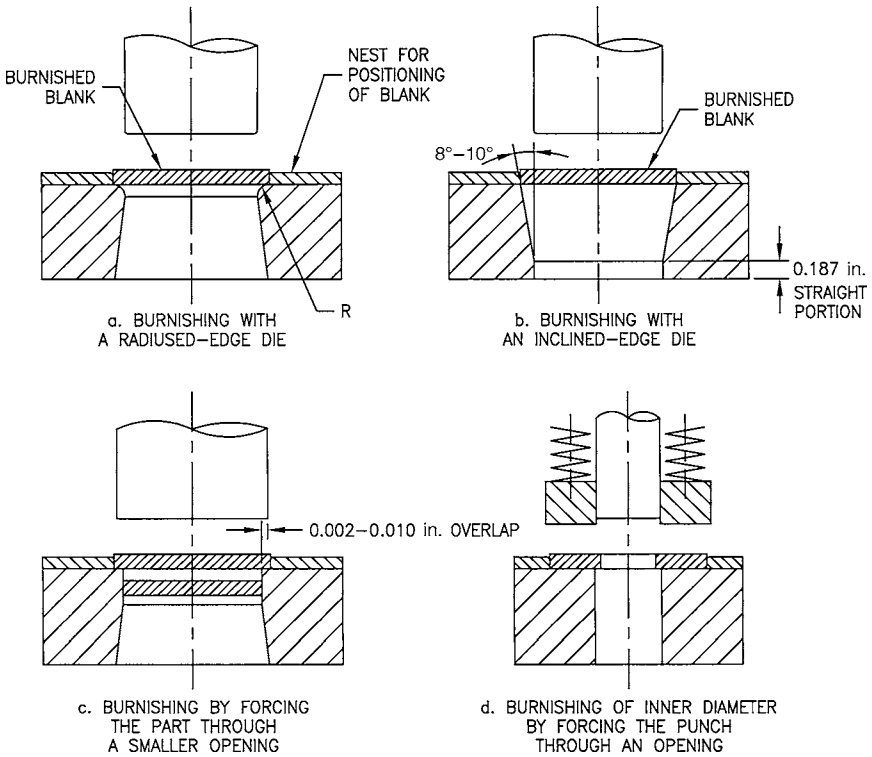
BURNISHED BLANK
NEST FOR POSITIONING OF BLANK
R
a. BURNISHING WITH A RADIUSED–EDGE DIE
BURNISHED BLANK
8°–10°
0.187 in. STRAIGHT PORTION
b. BURNISHING WITH AN INCLINED–EDGE DIE
0.002–0.010 in. OVERLAP
c. BURNISHING BY FORCING THE PART THROUGH A SMALLER OPENING
d. BURNISHING OF INNER DIAMETER BY FORCING THE PUNCH THROUGH AN OPENING

FIGURE 3-31 Burnishing methods.

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METAL STAMPING DIES AND THEIR FUNCTION

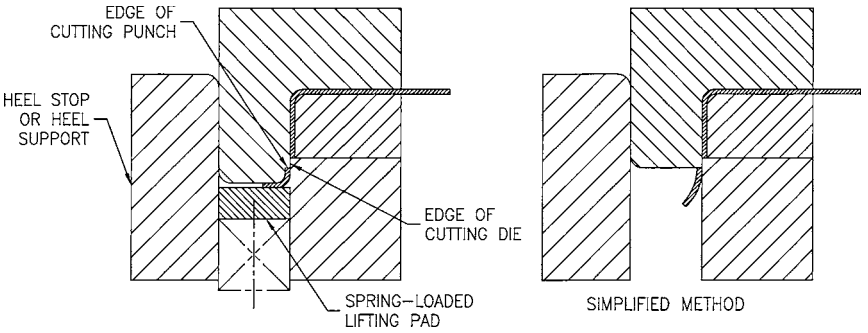

FIGURE 3-32 Pinch trim.

Where the inner surface of an opening is of concern (as shown in Fig. 3-31*d*), the burnishing tool does not have to be a punch-type instrument, nor it has to cut through the hole. This type of burnishing can be achieved by using a tapered punch that does not cut, but rather smoothes the sides of the opening to attain the needed precision, location, shape, or surface finish.

For burnishing, material must be added to the part's outline, approx. 0.006 to 0.016 in. (0.15 to 0.40 mm) per side. With complicated shapes, these values should be doubled.

A process used for trimming of rough or uneven edges of drawn cups is called *pinch trimming* (Fig. 3-32). Unfortunately, despite all good intentions, a pinch trim cut usually comes out slightly squeezed, as shown earlier in Fig. 1-14*c*.

Trimming With Brehm's Shimmy Dies®. Shimmy Dies represent quite an unique approach to metal trimming, which mostly everyone considers parallel to the action of the press ram, or up and down. This is true, with the exception of cam movements, of course. Shimmy Dies are another such exception. Here the sideway action of the die can trim the edges of simple or complex parts, as shown in Fig. 3-33.

FIGURE 3-33 Parts trimmed with a Brehm's Shimmy Die®. (*Reprinted with permission from Vulcan Tool Corporation, Dayton, OH.*)

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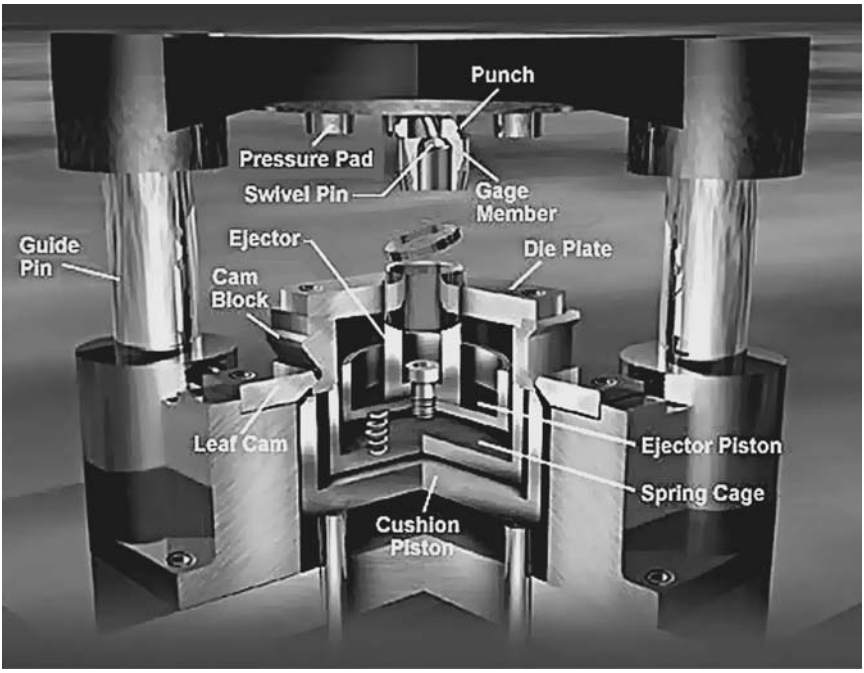

FIGURE 3-34 Cross-section of a Brehm's Shimmy Die®. (*Reprinted with permission from Vulcan Tool Corporation, Dayton, OH.*)

With each stroke of the press, the pressure pads pushes the die block down, along with a part-to-be-trimmed (see Fig. 3-34). At the same time, a series of cams are activated, which drive the die block toward a stationary punch, in four directions. This way, the punch cuts through the circumference of the part, or through any outline thereof, from inside out. The burr on the cut surface is negligible and the material thickness at the trimline is 100 percent of what it was before.

In the first stage of the cut (see Fig. 3-35, item no. 1), the trimmed material goes through a plasticlike state, as the punch enters its mass. Under the cutting force, the material at first stretches, which produces a small radius around the cut edge. In step no. 2, a shear is shown, which usually occurs in about 30 to 50 percent of the wall thickness. The break issues when the shear strength of the material is exceeded, with the resulting scrap being severed off.

There are one- and two-motion cam dies used, that can perform one of the two trim steps; a four-motion trimming die can do the entire trimming operation in a single station, during a single stroke of the press. Rectangular parts should have their corner radii at least five times the material thickness, which allows for a total coverage of the corners, as shown in Fig. 3-36.

With the ascend of the press ram, the trimming operation is complete and parts, along with thus removed scrap, can be air-ejected or otherwise removed from the die surface.

The thickness of the trimmed material can range from .005 to .250 in. (0.13 to 6.35 mm). Overall sizes of parts can be ¼ in. (6.3 mm) and up, up to 5 feet (1.5 m), with a variety of material such as brass, aluminum, steel, stainless steel, titanium, and inconel. The overall height tolerance (from inside of the part) can be held within a few thousandths of an inch.

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METAL STAMPING DIES AND THEIR FUNCTION

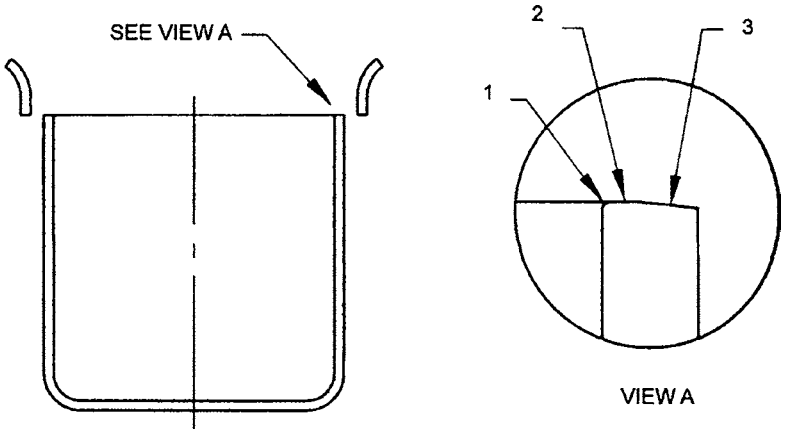

FIGURE 3-35 A three-stage process of trimming with a Brehm's Shimmy Die®. (*Reprinted with permission from Vulcan Tool Corporation, Dayton, OH.*)

Shimmy dies can be adapted to accommodate shape variations, bent-up parts, or long tubing. They can be setup as complete machines, with their own electrical, hydraulic and pneumatic systems, if automation of the process is required. Horizontal type of dies (shown) can be punch press or hydraulic press-driven.

3-3-2 Bending and Forming Dies

Bending dies are used to form, fold, or offset parts without subjecting their material structure to the flow and plastic deformation. Aside from simple bending dies, this type of tooling includes: curling dies, twisting dies, and straightening or flattening dies. Forming dies, however, belong into this category only marginally, as they fit in with the drawing dies as well.

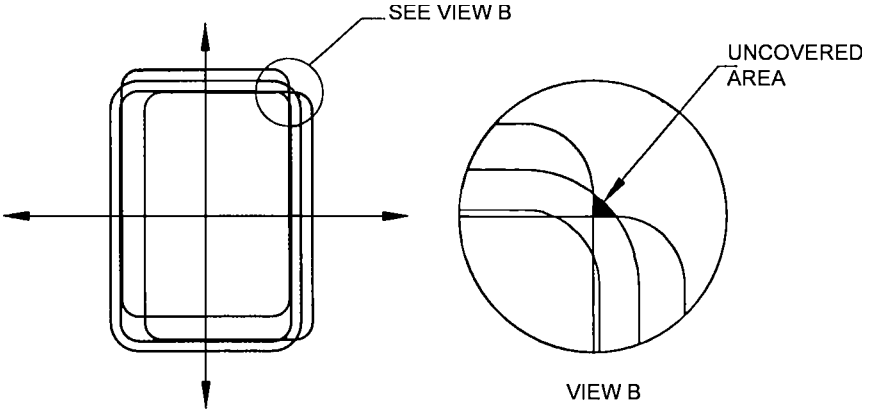

FIGURE 3-36 Cutting of rectangular parts with Brehm's Shimmy Die®. (*Reprinted with permission from Vulcan Tool Corporation, Dayton, OH.*)

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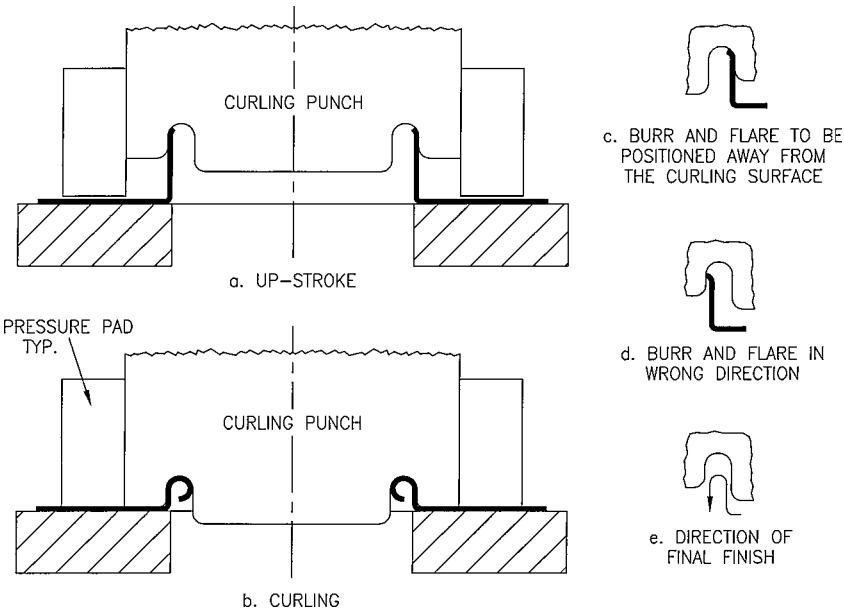
CURLING PUNCH
a. UP–STROKE
PRESSURE PAD TYP.
CURLING PUNCH
b. CURLING
c. BURR AND FLARE TO BE POSITIONED AWAY FROM THE CURLING SURFACE
d. BURR AND FLARE IN WRONG DIRECTION
e. DIRECTION OF FINAL FINISH

FIGURE 3-37 Curling operation, the first type.

Bending dies deform a flat part into an angular shape. The bend line is straight, with no plastic deformation present. *Forming dies* deform a flat part in much the same manner, but the line of a bend may be curved, with plastic deformation evident in some areas surrounding the curvature.

Curling dies form the edge of a part into a circular, hollow ring, as shown in Fig. 3-37. Sometimes a wire can be installed in such a shape. Common representatives of curled parts are hinges and edges of some containers.

This type of curling is burr-side sensitive. The burr should never be positioned against the curling surface (see Fig. 3-37*c*), since it may become entrapped in some minute imperfection of it, produce scratches, or otherwise cause damage during the curling process. Such a complication may easily obstruct the development of a curl and even ruin the tooling.

Sometimes a flare in the material's edge needs to be provided to ease the curling. Where materials of different properties are to be formed in the same tooling, variations in the curl's shape and size may be encountered. The curling groove is further dependent on the thickness of formed material, as shown in Table 3-6.

In the case a larger than necessary diameter of the curling die is used, the material will ignore its guidance and form a curl of its own, smaller in size.

Curling dies should be made of hardened tool steel, since they suffer from a great amount of wear. The grooves must be very smooth and well polished to aid a uniform sliding movement of the material. Even though the grooves will be most often produced using conventional machinery, the final polishing should be done in the direction of curling, as shown in Fig. 3-37*e*. This is to prevent the curled metal material from being obstructed by the grooves which invariably remain on the material's surface after the lathe work.

Normally, curling dies run in presses with long strokes, since the length of the curl must be in congruence with the travel of the ram.

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TABLE 3-6 Recommended Curling Diameter

Stock thickness		Recommended curling diameter	
in.	mm	in.	mm
0.010	0.25	0.062–0.078	1.60–2.00
0.018	0.50	0.125–0.156	3.20–4.00
0.030	0.75	0.203–0.250	5.15–6.35
0.420	1.00	0.281–0.343	7.15–8.70

With another type of curling which is performed in three successive steps, the tooling of the first stage should produce bends in the sides, as shown in Fig. 3-38*a*. These formed portions should be brought as close to 90° as possible. The second station produces the bottom bend, which, aided by the shaped sides of the die, forces the two preformed edges against the body of a punch. The third station is but a closure of the ring.

This type of curling depends on the accurate development of the blank. If excessive material is found in the final curling stage, buckling, and deformation, with possible overlapping can result. With too little material used, the circle will not close and sometimes the shape may not be properly formed.

Twisting dies can twist the strip material. A slight plastic deformation may be evident in this operation.

3-3-3 Drawing Dies

Drawing dies force the material to flow in conjunction with the movement of the punch, which causes plastic deformation to its structure. During the drawing process, the volumnar amount of flat blank is transformed into a drawn, shell-like shape. In some cases, thinning of the part's cross section may be observed. The category of drawing dies consists of drawing, redrawing, ironing, reducing, and bulging dies (Figs. 3-39 and 3-40).

Ironing dies function on the same principle as drawing dies. The only difference is the clearance between the drawing punch and the die, which in ironing dies is smaller. The diminished gap between the tooling forces the drawn shell to become thinner, while smoothing the shell's wall surface at the same time.

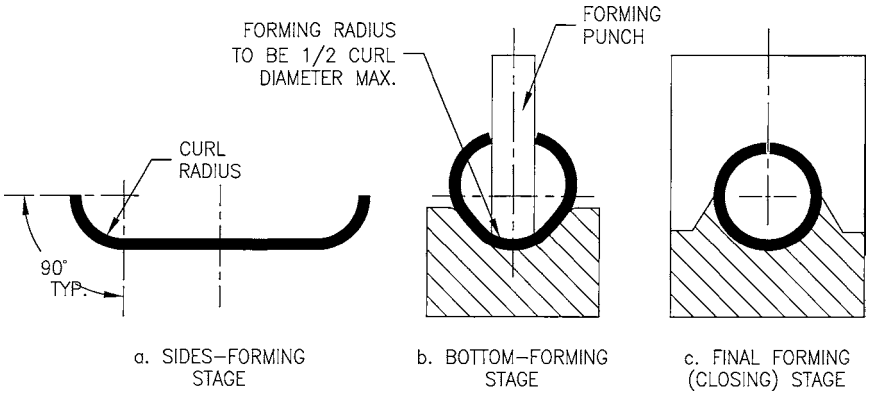

FIGURE 3-38 Three-stage curling operation.

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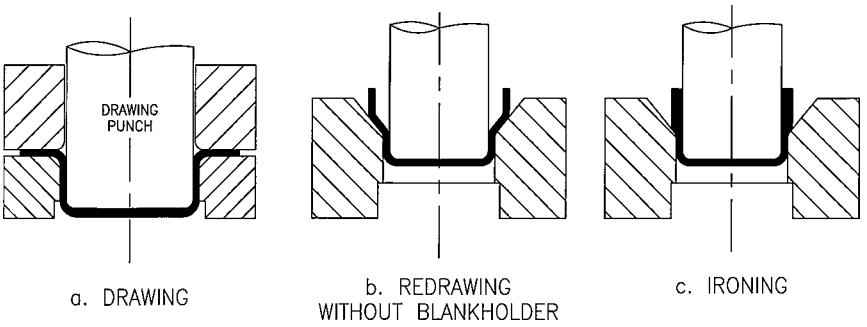

FIGURE 3-39 Drawing, redrawing, and ironing.

Bulging dies (Fig. 3-40) expand a drawn shell from the inside, to conform to the shape of the die. There are two kinds of bulging dies: those utilizing rubber as an expanding material and those using water or other fluids. The latter are also called *fluid dies*.

Parts bulged with rubber inserts display a uniform and smooth surface, but the disadvantage of this medium is that it wears out quickly. Probably because of the continuous expansion and contraction, aided by the corrosive effect of lubricants, the rubber material tires out, and easily deteriorates.

Where fluid is used as an expanding medium, the parts are free of tool marks, and their walls are of even thickness with no thinning even in radiused areas. The metal necessary for the expansion of shape is taken from the height of the shell, rather than utilizing its thickness for that purpose. Only when bulging with a retaining flange added on top produces

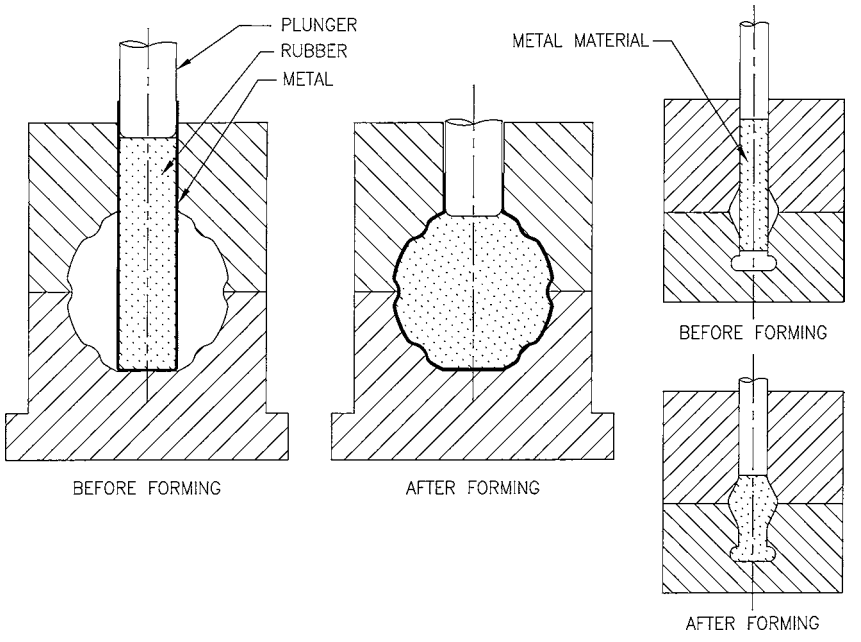

FIGURE 3-40 Bulging process.

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METAL STAMPING DIES AND THEIR FUNCTION

bulges that do not decrease in height. Naturally, in such a case, walls of the bulged part come out thinner.

The forming liquid is forced into the bulging die under a pressure, the amount of which is dependent on the thickness and properties of formed material. It is advisable to begin forming with a lower pressure and increase it gradually, as needed. Otherwise, if the pressure should become excessive, the shell may burst open.

The bulging die consists of two halves, which are taken apart for removal of the finished part.

The expected circumferential increase should be about 30 percent in a single operation. Any bulging greater than that has to be performed in stages, often with annealing of the bulged material in between.

Rubber and Fluid Forming. In rubber forming, the rubber pad is attached to the ram of the press, and on coming down, it forces the flat sheet to conform to the shape of the form block underneath it. Even though the rubber is mostly flat, it can take on any shape, and a single rubber pad can therefore be used to form parts of various shapes.

The pressure, which the rubber pad exerts on the metal is uniform, so that the forming process creates no thinning of the walls or radii. The radii are, however, more shallow than those produced in conventional dies.

The disadvantage of this method of forming is that rubber easily tears. The continuity of expansion and contraction also places a great strain on this material, subjecting it to greater than usual wear.

Several processes utilize the rubber pad forming techniques, described as follows:

- Guerin process (Fig. 3-41), in which the pad is a fairly soft rubber block, either solid, or assembled from laminated slabs. The height of the block is usually three times the depth of the formed part. It is contained in a sturdy cast-iron or steel retainer, as the forming pressures may be as high as 20,000 lb/in.^{2} in some applications.

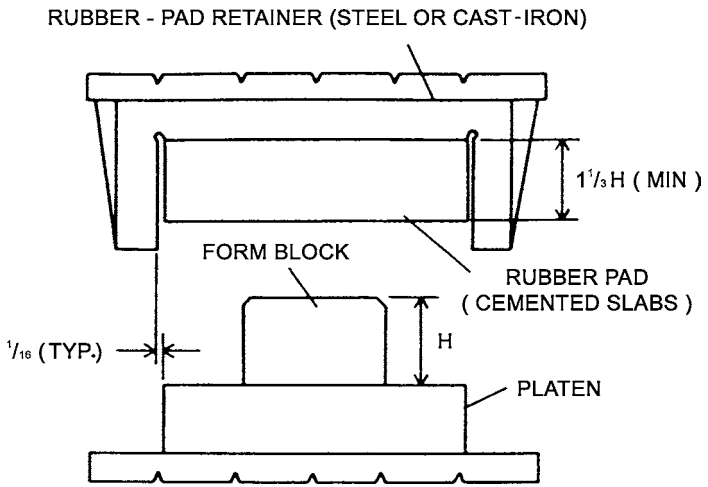

FIGURE 3-41 Guerin forming process, tooling, and setup. (*From: O.D. Lascoe, "Handbook of Fabrication Processes," ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

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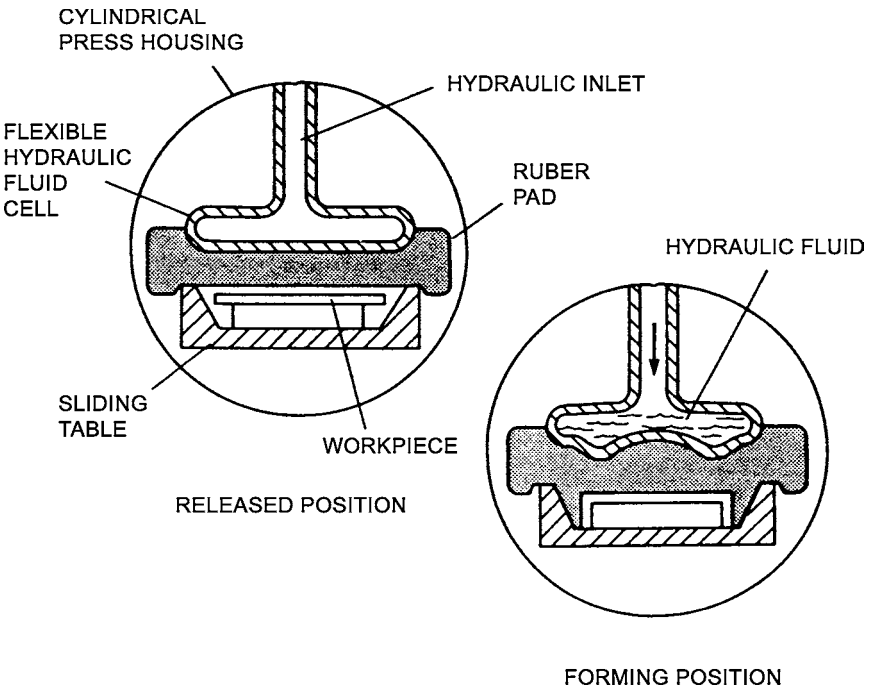

FIGURE 3-42 Verson-Wheelon forming process principle. (*From: O.D. Lascoe, "Handbook of Fabrication Processes," ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

- Verson-Wheelon process (Fig. 3-42) is based on the previously described Guering process, with higher forming pressures supplied by a flexible hydraulic device. The pressure is applied toward the rubber pad, which may serve as either a punch or a die, and it is uniformly distributed all over its surface. Such well-distributed pressure allows for formation of wider flanges, shrink flanges, beads, ribs joggles, and the like. These formations display rather a sharp detail, be they made of aluminum, low carbon steel, or even titanium steel. However, the parts produced by this process are limited in depth.
- Marform process (Fig. 3-43) presents yet another utilization of the cheap tooling used in the Guerin and Verson-Wheelon processes. However, here it can be utilized to produce deep drawn parts, or to form wrinkle-free shrink flanges. The rubber pad is thick, aided by a hydraulic cylinder, whose function is controlled by a pressure-regulating valve. The blank is retained firmly between the blankholder and the rubber pad. With the application of pressure, it is forced to conform to the shape of the form block underneath.

Aside from the rubber block, the main part in this type of forming is the form block. Form blocks can be made of wood, masonite or aluminum, kirksite, and similar materials. The blank is positioned on the block with at least two locating pins, whose height should not obstruct the action of the rubber pad. Some forming blocks and auxiliary forming tools are shown in Fig. 3-44.

Stretch flanges (Fig. 3-45*a*) can be easily and quite accurately formed with the rubber forming process. In this case especially, such a production technique is more economical than that utilizing regular hard tooling. Shrink flanges (Fig. 3-45*b*) are more difficult to fabricate, and without various mechanical forming aids such as those shown in Fig. 3-44, their production would be quite difficult.

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METAL STAMPING DIES AND THEIR FUNCTION

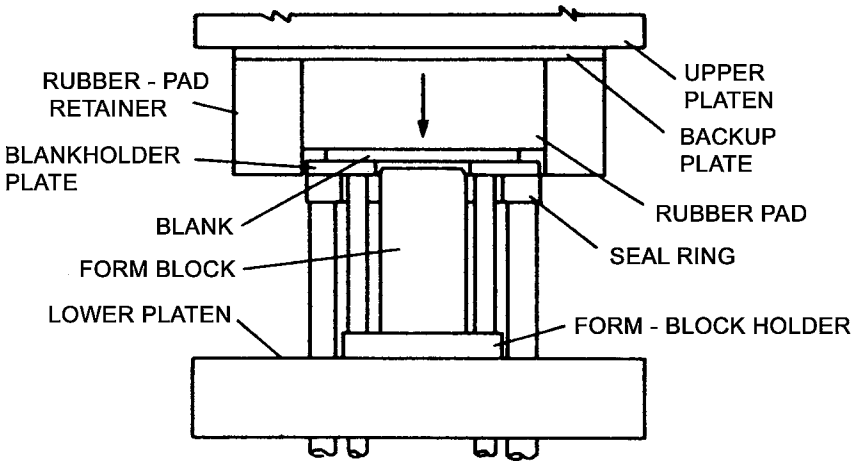

FIGURE 3-43 Marform forming process, tooling and setup. (*From: O.D. Lascoe, "Handbook of Fabrication Processes," ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

Fluid forming is similar to rubber forming, but here the rubber is replaced by the forming fluid, most often oil. It is a useful method utilized for the production of complex parts fast and economically. Basically, there are three types of fluid forming: forming in a die cavity, forming over a rigid punch, and expanding or bulging.

- Fluid forming in a die cavity (Fig. 3-46). The forming unit consists of a rubber diaphragm filled with oil and acting under hydraulic pressure on the flat piece of metal positioned

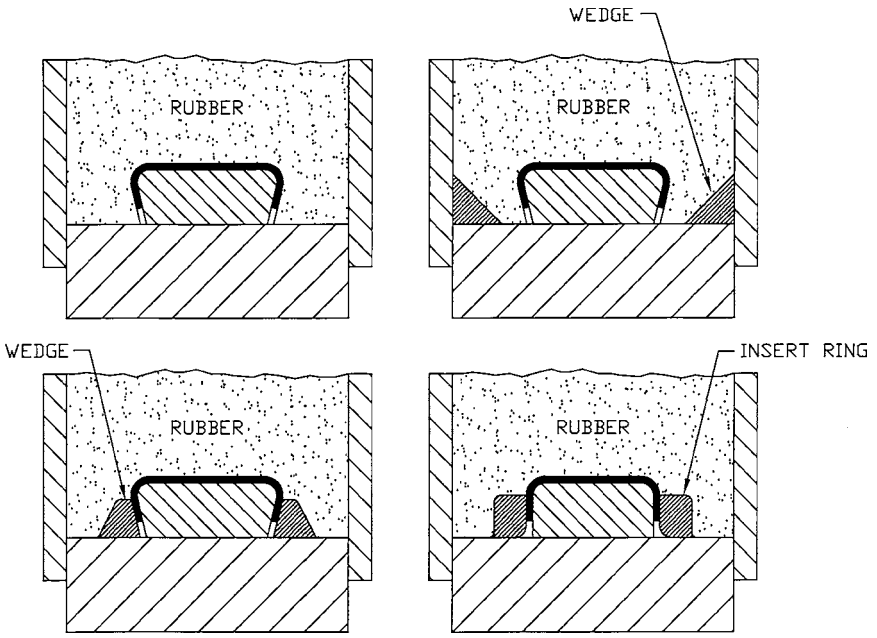

FIGURE 3-44 Forming with rubber.

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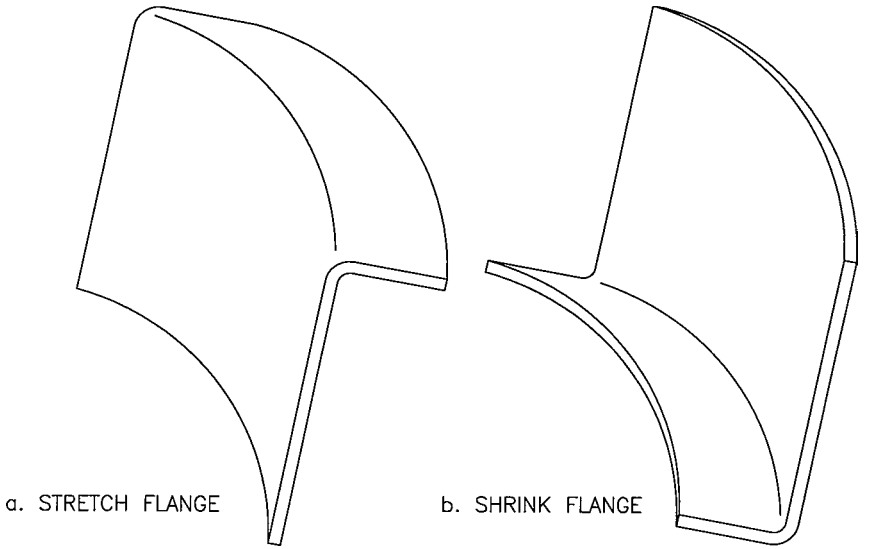

FIGURE 3-45 Stretch and shrink flanges.

over the die cavity. At the end of the cycle, the formed part is blown out by compressed air coming in through the bottom of the die.

- Fluid forming over a rigid punch (Fig. 3-47) utilizes a principle similar to the previous example. Here the system of valves allows for a variation of the blankholder pressure during the work cycle. The blank, positioned on the draw ring, is wrapped around the punch (i.e., form block) on the descent of the ram.

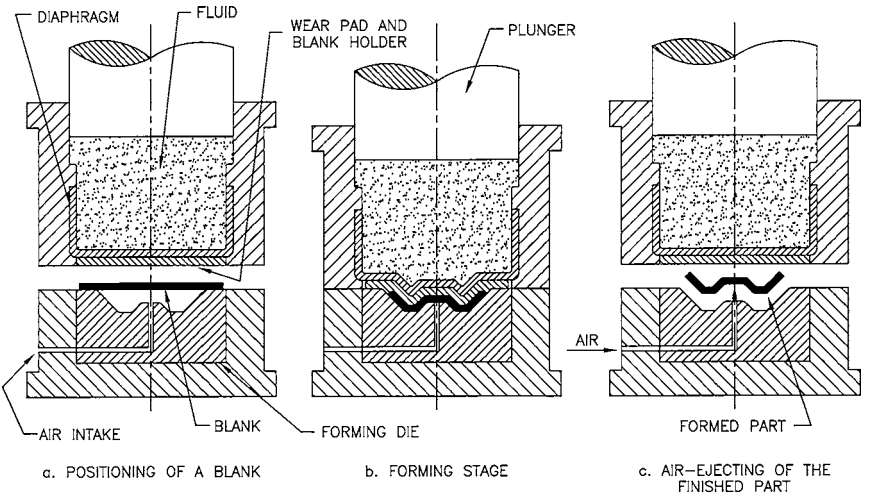

FIGURE 3-46 Fluid-forming in a cavity die.

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METAL STAMPING DIES AND THEIR FUNCTION

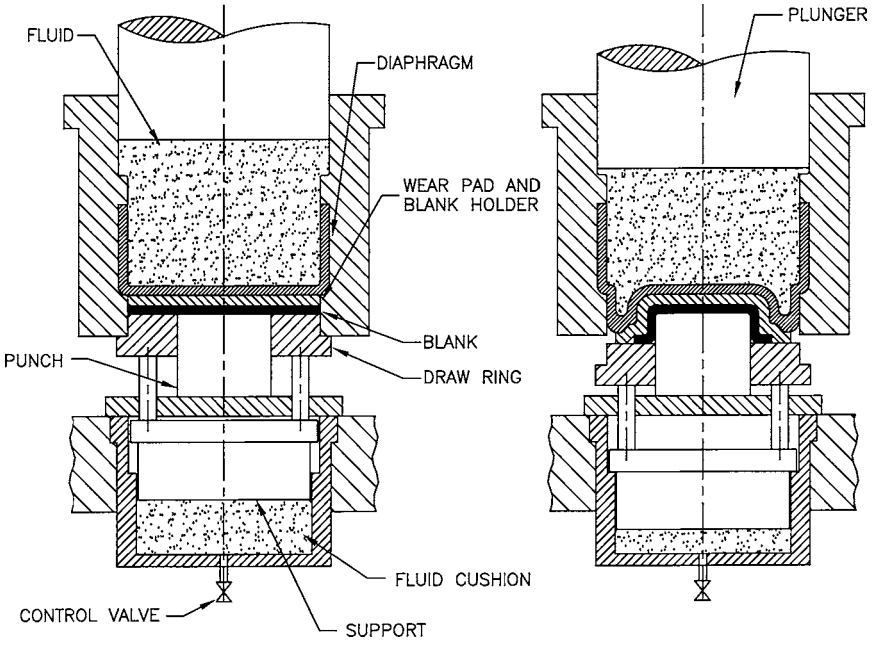

FIGURE 3-47 Fluid-forming over a solid punch.

- Expanding or bulging (Fig. 3-48) replaces the wear pad with an oil-filled rubber sack. During the forming cycle, the fluid pressure is transmitted equally in all directions. There is virtually no springback on the part, because the fluid acts simultaneously as a sizing element.

Additional types of specialized forming dies are *reducing dies*, often called "swaging" *or* "necking dies" (Fig. 3-49). These are the exact opposite of bulging dies. Here the shell is reduced in diameter, with subsequent elongation of its length.

The advantage of this operation lies in the fact that the shape is altered without any need for machining the material away, which eliminates the necessity of additional finishing operations.

3-3-4 Compressive Dies

Compressive dies force the material to flow into a cavity and fill all its crevices. These dies are called coining, embossing, extruding, impact extruding, forging, heading, riveting, upsetting, and staking dies.

Embossing (Fig. 3-50) is a metal stretching and compressing operation, already described in Sec. 1-3-2.

If an embossing operation is to be included in a progressive die sequence, it should be placed at one of the beginning stages, since the emboss will draw the metal needed for its shape from its immediate surroundings, which may affect the final outline of the part.

Coining dies (Fig. 3-51*a*) are cold-forming tools which force the material into a structural cavity by exerting a considerable pressure on it. The metal is squeezed, with resulting displacement of its portions, until it fills the whole cavity.

Heading, riveting, upsetting, and staking dies are cold-forming tools which force the material to take the desired form (see Fig. 3-51). These operations are similar in their outcome, even though they produce parts for different applications. Heading is used to form screw heads and

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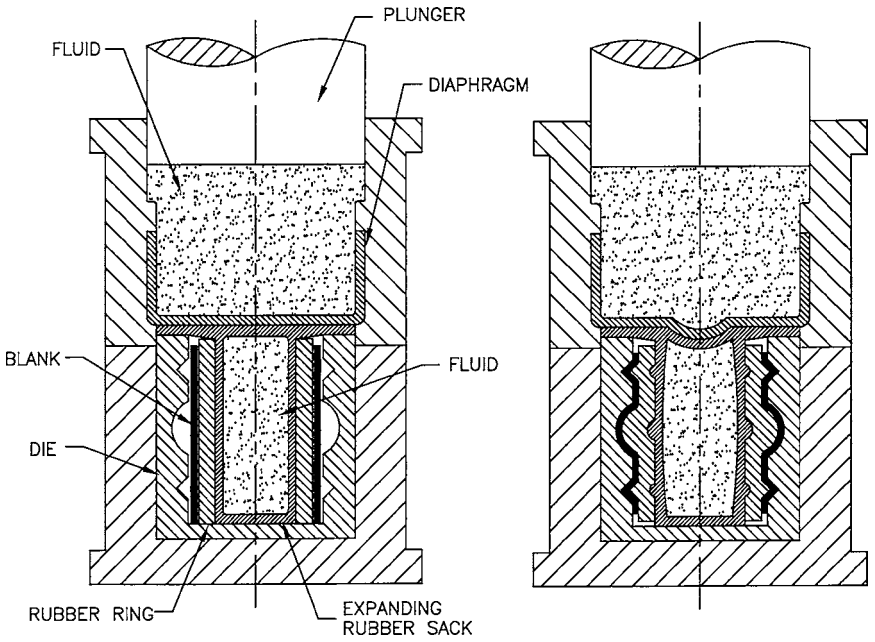

FIGURE 3-48 Bulging with fluids.

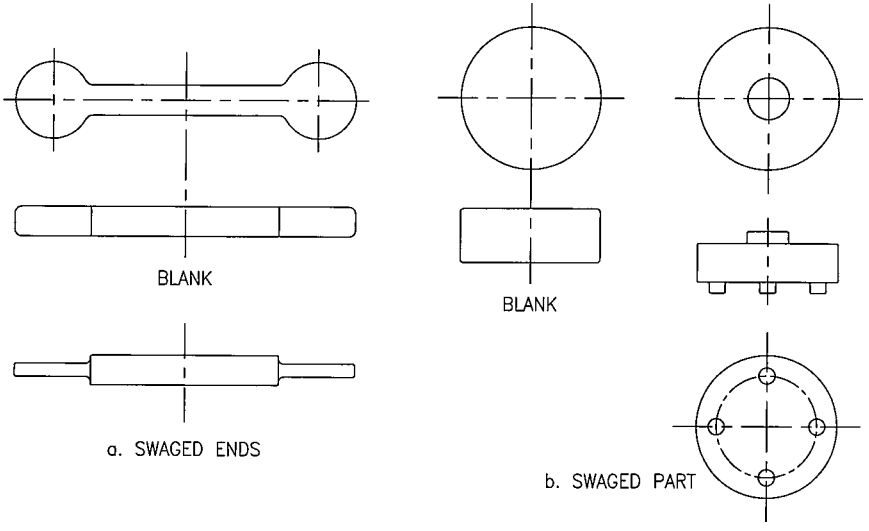

FIGURE 3-49 Examples of swaging process.

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METAL STAMPING DIES AND THEIR FUNCTION

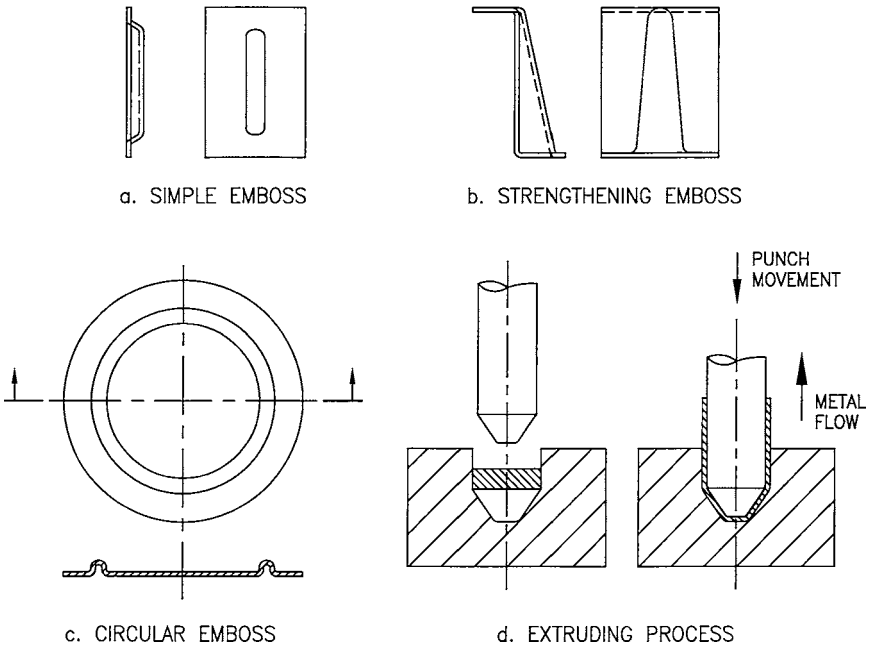

FIGURE 3-50 Embossing and extruding.

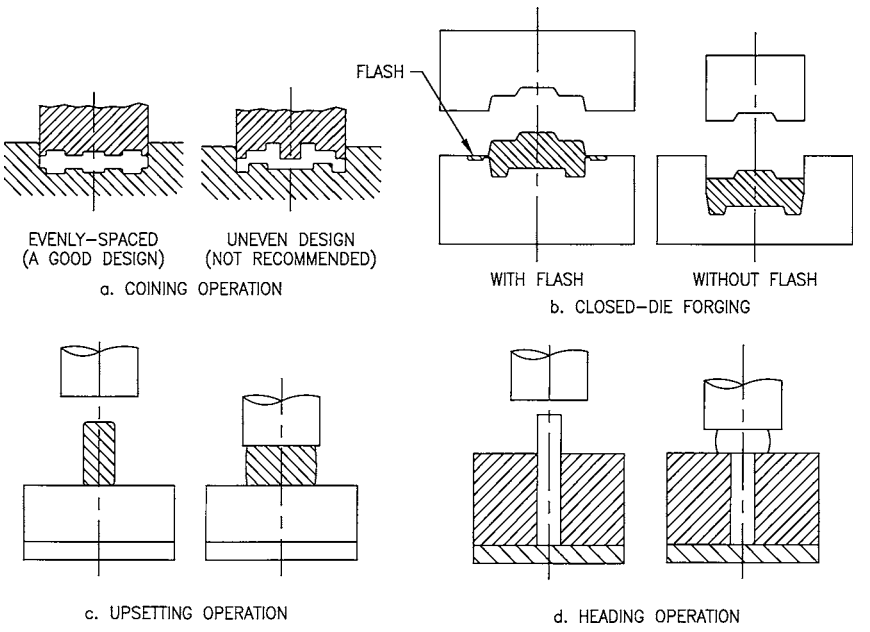

FIGURE 3-51 Coining, forging, upsetting, heading.

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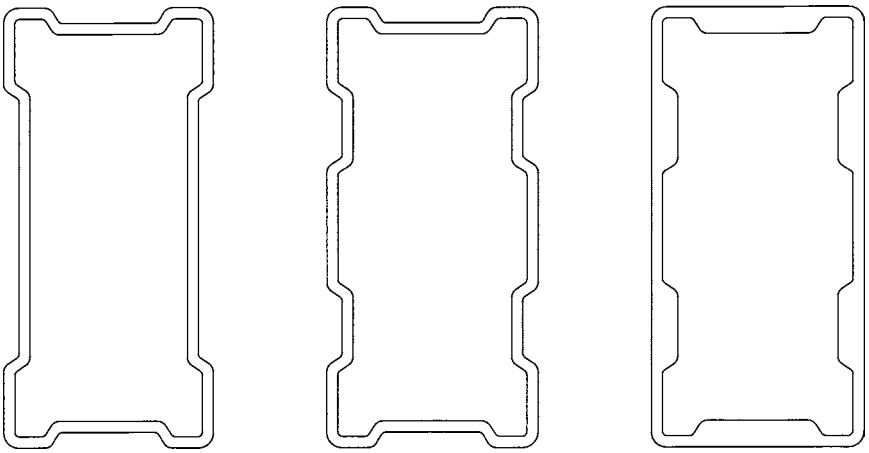

FIGURE 3-52 Impact extrusion: cross-section of parts.

similar. According to its functional aspects, it may also be called open die forming. Upsetting, on the other hand, is quite close to the forging process, and may also be defined as free forming.

The upset ratio in a part must be proportioned in order to limit buckling, as:

$$0.5 = \frac{l_0}{d_0} = 2 \tag{3-3}$$

where l_0 is the initial length and d_0 is the initial diameter.

Extruding dies can form a flat piece of metal into a tubelike shape by first forcing it into the cavity, and shooting it up by the pressure of the extruding punch (Fig. 3-50*d*).

Impact extrusion (Figs. 3-52 and 3-53) is used for the manufacture of hollow, thin-walled, and deep recessed parts. With dependence on the type of metal, it can be produced from cold slugs, as well as at elevated temperatures. Aluminum alloys, tin, and lead are formed cold, while zinc uses elevated temperatures around 300°F or 150°C.

Forging dies are similar in obtained results to the impact extrusion process, with the only difference being the source of the pressure on the part, which in this case is mostly a hammer dropped down on the workpiece.

There are two kinds of *drop-hammer forging: gravity-hammer forging* and *double-action hammer forging*. Gravity-hammer forging depends on the weight of the hammer, which is lifted to certain height and allowed to fall on the workpiece. The double-action hammer is accelerated in velocity during its fall by an addition of steam or air pressure.

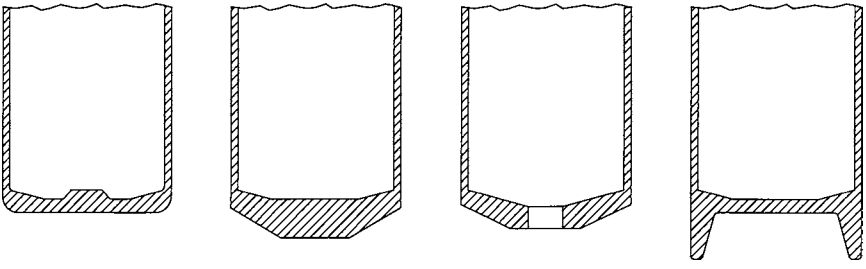

FIGURE 3-53 Shapes of bottoms in impact extrusion.

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METAL STAMPING DIES AND THEIR FUNCTION

Forging dies can run hot or cold. Hot forging achieves the deformation of the blank with a single stroke of the hammer. Cold forging, even though called "cold," is actually exposed to certain thermal influences as well, these being induced by the forming action on the metal.

In forging, the entire volume of the flat blank is forced into a die cavity. Closed forging dies with no flash can actually be called coining dies (see Figs. 3-51a and b). The exact volume of metal blank must be well calculated for this operation, as there is no provision for the excess to flow out of the die and turn into a flash.

3-3-5 Miscellaneous Dies

Miscellaneous dies include marking and numbering dies, straightening or flattening dies, horn dies, cam dies, hemming dies, crimping dies, assembly dies, and subpress dies.

Marking and numbering dies are used for stamping numbers, characters, and symbols on metal parts.

Straightening or flattening dies will bring a part to size, or a drawn shell within the drawing dimensions by striking it without allowing for its walls to become thinner.

Horn dies are equipped with a horn, which is a sort of protruding stake, or a mandrel, the shape of which conforms to the inner configuration of the part. Drawn or formed parts can be positioned over the horn for the application of secondary operations. Finished products may be stripped off by the action of springs, cams, levers, or air-blowing devices. Sometimes the stripping arrangement may be dependent on the movement of the ram.

Cam dies transform the vertical motion of the die movement into a horizontal (or angular) movement. With the aid of cam dies, many side-piercing operations can be performed.

The cam and horn die in Fig. 3-54 utilizes the spring-loaded movement of the forming tool (i.e., slide, one for each side of the part), while the spring-dependent horn supports the formed part. On lowering of the upper die member, the horn engages the part, and soon afterward the cam driver (one on each side) pushes the sliding-form tool toward the part to be formed. The slide is restricted from other than intended movements by the gib. The gib assembly is usually made of hardened and ground tool steel. Sometimes the slide mechanism may contain an additional hardened wear plate, located underneath its body.

The cam driver may be constructed of tool steel, cold rolled steel, or just iron, and it may be welded together from pieces. The work-angle must be between 20° and 40° off the vertical (see Fig. 3-55), which should not be exceeded in either way. Generally, the closer the driving angle is to the vertical, the better the mechanical function of the cam mechanism will be.

Hemming dies can fold an edge of a sheet-metal piece back onto itself, which is often used as an edge reinforcement (Fig. 3-56).

Crimping dies are used to create additional surfaces to be used for retention of other parts and assembling them together. These dies operate by bending, denting, louvering, or otherwise forming the retaining shape. In Fig. 3-57, a flange of the first cup is crimped over the second cup for closure and retention.

Assembly dies are built to assemble various parts, and they utilize riveting, staking, forming, press-fitting, and similar operations.

Subpress dies, or *self-guiding dies* (Figs. 3-58 and 3-59), are valued for their great accuracy in punching out minute, precise parts, such as watch hands, geared wheels, and watch dials. There are two types of these dies: the cylindrical subpress and the pillar-type subpress.

The *pillar-type subpress die* uses pillars for the support and guidance of its movement. In the *cylindrical subpress die* the up-and-down moving plunger is guided by a bearing surface, which is firmly attached to the sturdy casting of its body.

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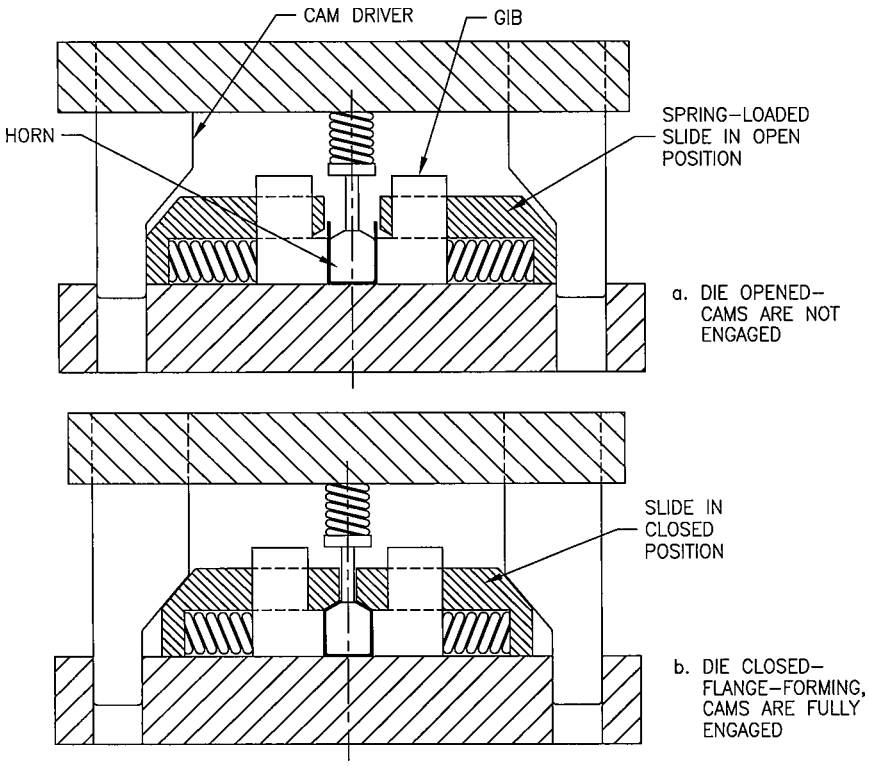
CAM DRIVER
GIB
HORN
SPRING–LOADED SLIDE IN OPEN POSITION
a. DIE OPENED– CAMS ARE NOT ENGAGED
SLIDE IN CLOSED POSITION
b. DIE CLOSED– FLANGE–FORMING, CAMS ARE FULLY ENGAGED

FIGURE 3-54 Cam and horn die.

3-4 NEW METHODS IN METALWORKING

Metal-forming techniques, as recognized today, are too often being scrutinized for possible improvement. New processes, new manufacturing techniques, new equipment—these all are continuously experimented with, in an attempt to improve the existing manufacturing results. In other words, whatever was good enough yesterday, is not satisfactory today.

These new means of manufacturing brought sometimes quite surprising results: for example in the field of materials' superplasticity, an elongation of over 4000 percent was achieved, with no thinning or necking of the material. Forming with superimposed vibrations cut the needed press tonnage to unbelievably low ranges.

However, not all new processes are yet adaptable to our present situation. Many may seem to be promising in their outcome, but the conditions for arriving at such results are not always acceptable. Vibrations may lower the press force required for bending the metal, but their influence would reach far beyond that steel affecting the manufacturing equipment and tooling, manufacturing personnel, and perhaps even the structure of buildings—who knows?

Many of these techniques are too new for their long-term effects to be known. Only time can evaluate these processes and choose the most appropriate combination of manufacturing ease and human or equipment tolerance.

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METAL STAMPING DIES AND THEIR FUNCTION

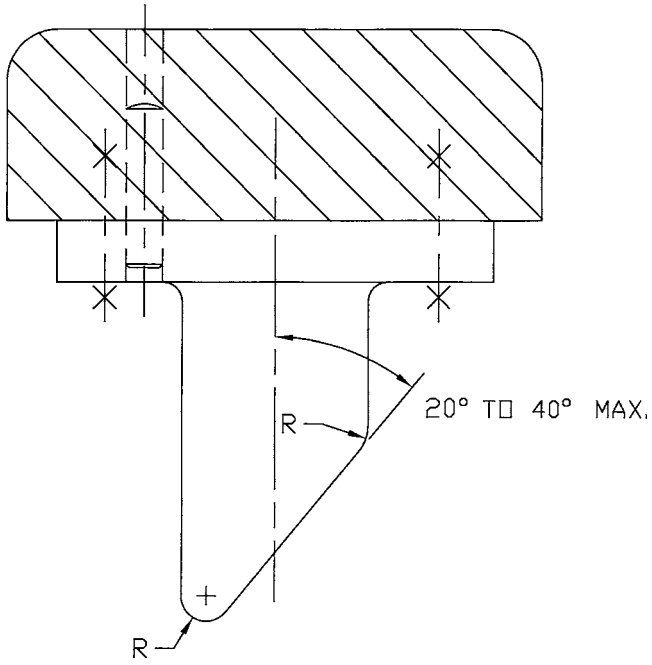

FIGURE 3-55 Cam driver detail.

3-4-1 Electromagnetic Forming

During the process of electromagnetic forming, the energy stored in condenser batteries is released in the form of electric impulses. These are guided through the coil, which is placed within the part to be formed. With smaller parts, the part is placed inside the coil.

The pulsating impact of the current creates a primary magnetic field around the coil, turning it into the forming (or cutting) tool. On introduction, the turbulent current forms a secondary magnetic field around the part to be formed. A reaction between these electric fields brings about the part's change of shape.

Such a forming process is carried out without any physical contact between the tool and the workpiece. Therefore, no tool marks are left on the formed part and there is no friction or surface contamination. The magnetic field affects only electrically conductive materials, which may be considered of advantage.

The forming pressure is equal throughout the range of the field, but it is quite difficult to apply it uniformly to a part with openings, notches, or embosses. Because of the required forming frequency of above 15 kHz for steel materials, only objects larger than 12 in. (305 mm) can be formed.

3-4-2 Electrohydraulic Forming

In this process, the energy stored in capacitors is discharged over a spark gap located in a tank with water. This creates a sudden release of steam, which, along with ionization, creates a high pressure shock wave within the liquid. The die, containing the part to be formed,

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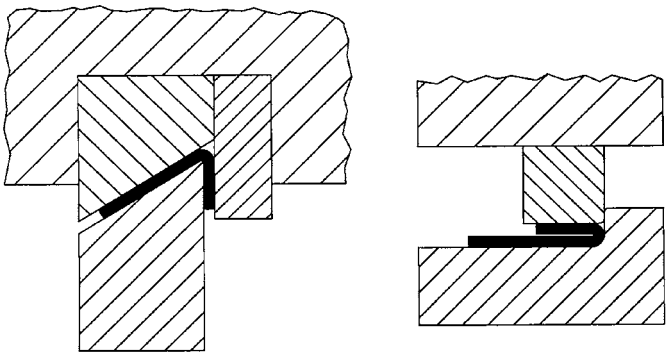
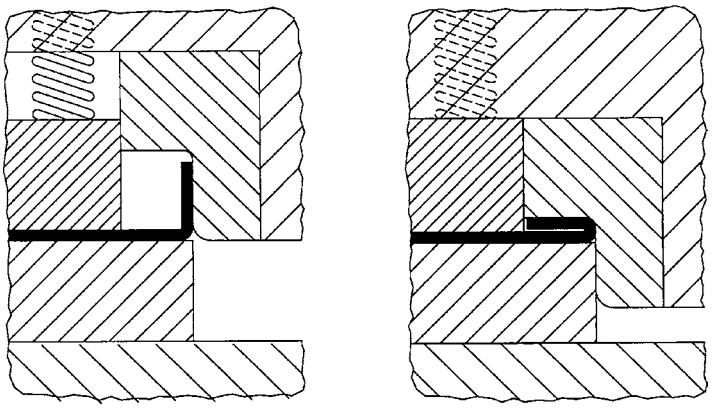


a. PRE–FORMING AT AN ANGLE
AND FINAL FORMING



b. PRE–FORMED FLANGE AT THE BEGINNING
AND THE END OF HEMMING OPERATION

FIGURE 3-56 Hemming operations.

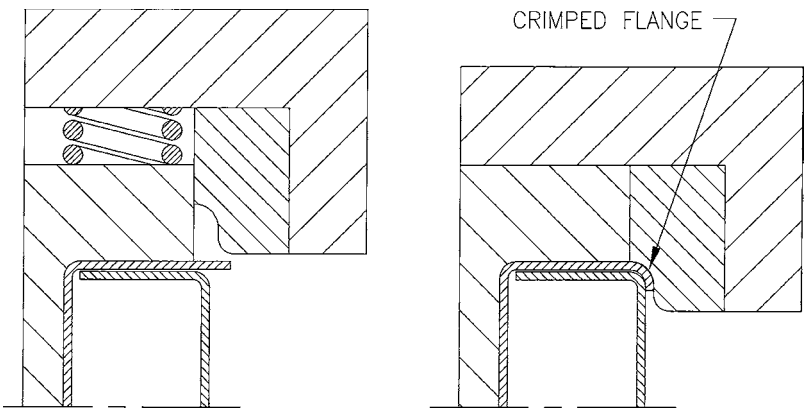


FIGURE 3-57 Crimping one shell over another.

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METAL STAMPING DIES AND THEIR FUNCTION

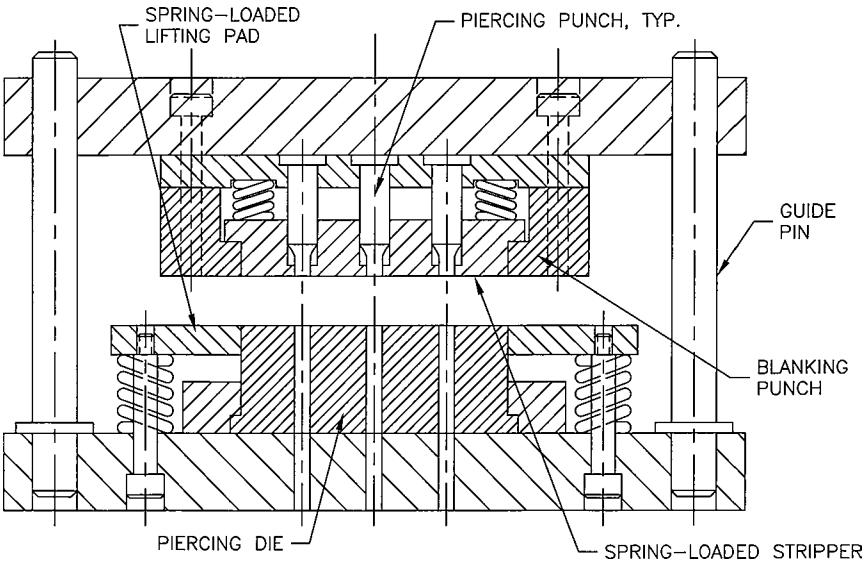

FIGURE 3-58 Section view of a pillar subpress die.

is immersed in the tank as well. When exposed to the shock wave, the part is forced to take on the shape of its die.

This process may be found useful for all tube-forming processes that alter the tube's profile and shape, such as complex forming, bulging, and expanding.

3-4-3 Forming With Explosives

Explosive forming is not really a new process, but very similar to electromagnetic forming described in Sec. 3-4-1. It has been around for years with differing results. Some consider it a superb method of manufacturing, others have lost their buildings to it in an explosion. It is a process in which safety cannot be overemphasized.

The energy, derived from explosives can be of tremendous intensity and the use of such force for forming processes is certainly tempting.

During the forming process, the explosive material, either in pieces or encapsulated, is placed in a water-filled tank alongside or within a die with the material to be formed. The charge, when detonated, prompts release of a great amount of steam and gas during a relatively short time interval. Such an action creates a strong shock wave in the liquid medium, which affects the part to be formed by forcing it to take on the shape of the die.

Objects suitable for utilization of such manufacturing process are mainly tubes, which may be bulged, expanded, or squeezed to tight tolerances and formed into uneven shapes. Metal plates may be drawn to wildest shapes, many of them unattainable otherwise.

3-4-4 Superimposed Vibrations

Ultrasonic waves, when applied to the molten metal, promote the development of additional currents within its mass, which in turn produce a more effective mixing, which results in an improved homogeneity of the metal. When applied to the metal as it begins to

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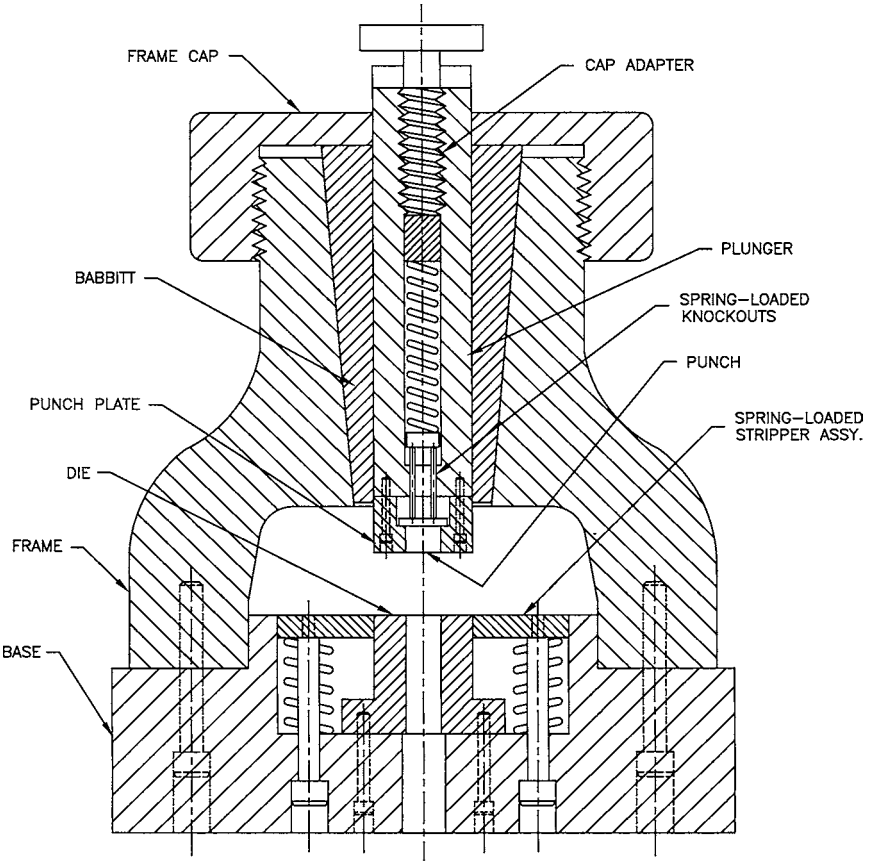

FIGURE 3-59 Cylindrical subpress die.

solidify, ultrasound dissolves microfractures, removes gaseous entrapments, and drives out impurities.

In solidified metals, high-intensity ultrasound repairs the structural defects by bringing the material into the stage of plastic deformation and rearranging its structure. Application of ultrasound reduces friction between metal particles, which in turn allows for a free movement of metal layers with respect to each other. This aids the forming process and improves homogeneity of the outcome. The speed of the forming is increased as well, with lessened friction between the material and its tooling, which subsequently decreases the wear of the latter.

Ultrasound enhances mechanical properties of materials, increases their hardness, prevents structural changes due to deformation, and lowers stresses caused by manufacturing processes, while improving the quality of the product's surface. Many brittle materials, such as bismuth, were possible to form only after ultrasound was added to the process. This is explained by the effect of vibrations on a metal crystal, which, under their influence, develops a series of linear defects, which lower its yield stress range.

When applied to the forming process, ultrasonic vibrations greatly reduce the amount of force necessary for the alteration of metal.

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METAL STAMPING DIES AND THEIR FUNCTION

However, this type of manufacturing is not widely practiced as yet. Its possible negative effects on the equipment, on the manufacturing personnel, and perhaps on the fabricated part has not yet been fully assessed.

3-4-5 Lasers and Their Application

Lasers operate on the basis of a concentration of their output to a small area of operation, approximately 0.002 to 0.010 in. diameter (0.05 to 0.25 mm). One of their advantages is the absence of contact between the tool (laser) and the workpiece.

The laser cutting process is fast, achieving high quality, burrless edges. The high temperature of the process quickly heats up the material in the path of the laser ray, causing the metal to melt and evaporate on contact. The surrounding material has no time to respond to such a sudden wave of heat, which is the reason for the cut surface's lack of distortion.

3-5 FINEBLANKING

Fineblanking is a special form of blanking, which not only produces finished edges on a cut part, but also works to close tolerances, attaining a superb consistency over high volumes of production. Fineblanking is performed in a cutting die, yet it is a process quite similar to cold extrusion.

In fineblanking (Fig. 3-60), the material to be pierced is firmly retained by a pressure ring, which, on descending of the ram, partially enters the material with its grips. The punch follows down, piercing an opening in the sheet. The pressure of the retaining ring is not

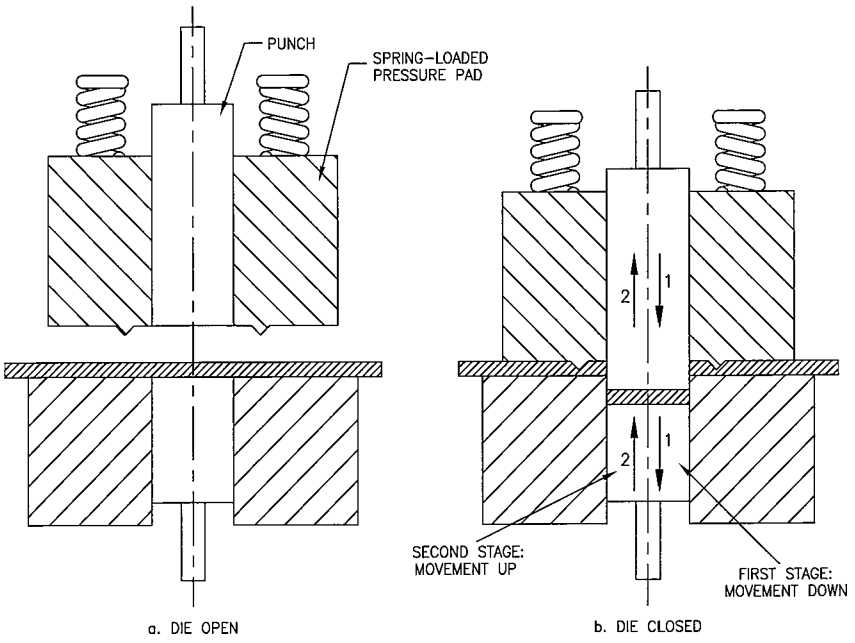

FIGURE 3-60 Fineblanking principle.

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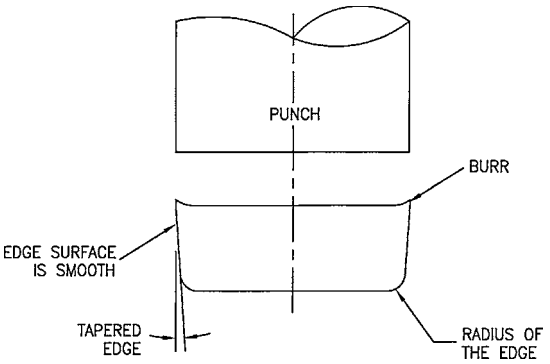

FIGURE 3-61 Fineblanked part.

immediately released. Instead a counterpressure to a die pad is applied, from the bottom. This pressure drives the blanked part up, along with the punch. At the die-bushing level, the pressure ring releases its grip on the metal and the blank can be ejected from the die by the still-rising bottom pressure pad.

This process uses tight clearances between the punch and the die, which amount to some 0.5 percent of the material thickness. While being taken down and up through the die, blanks have their cut edges forced into conformity with the surface of the opening. This smoothes the cut edge, making it even and uniform.

One possible disadvantage can be a tapered edge of blanked parts, which is due to a friction between the blank and the die opening. This taper is greater with thicker materials, or with those of higher carbon content. The burr appears on the punch side, while the opposite edge is rounded, as shown in Fig. 3-61.

One definite advantage is the high precision of the work. Openings of 0.125 in. diameter (3.18 mm) can be produced even in 0.187 in. (4.75 mm) thick sheet, with the hole tolerance ranging ±0.0004 in. (0.010 mm).

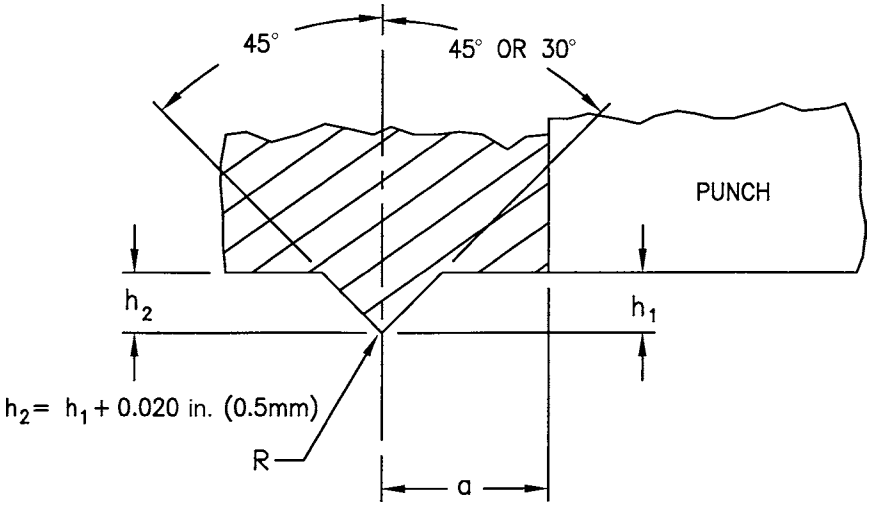

FIGURE 3-62 Shape of the grip.

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METAL STAMPING DIES AND THEIR FUNCTION

The work-retaining efficiency of grips is relevant to the quality of the cut. Their shape digs into the material before the punch descends to cut it. This in itself not only provides for controlled positioning of the sheet under the punch, but also stretches the sheet material in all directions, to prevent distortion.

The grips are most often located on the face of a pressure pad, bordering the punch along its entire shape. With materials thicker than 0.156 in. (4.00 mm), or where rounding of cut edges is to be kept to a minimum, additional grips may be located on the upper surface of the die.

The shape of the grip, as shown in Fig. 3-62, has two variations: either 45°–45° angles on both sides, or a 45°–30° angle combination. The height h_1 depends on the material thickness and its quality. It may vary along these recommended sizes:

$$h_1 = 0.167t \text{ for hard materials}$$
$$h_1 = 0.333t \text{ for softer materials}$$

The distance off the edge of the punch a depends on the height of the grip and its percentile value should be:

$$a = (0.6 \text{ to } 1.2)h$$

The height of the pressure pad behind the grip's edge is usually relieved, or:

$$h_2 = h_1 + 0.020 \text{ in. } (0.5 \text{ mm})$$

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CHAPTER 4
METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

4-1 TOLERANCING SYSTEMS

Manufacturing of parts cannot be absolutely precise. If such be the case, the cost of components would be horrendous. Already the differences in straightness or flatness, surface finish, the existence of tooling marks or tooling grooves, burrs, chips, and similar, can render the component unacceptable by too harsh a standard.

Yet, all these discrepancies can sometimes be present and for this reason designers and manufacturers devised a certain area of benevolent acceptance, called a *tolerance range*. This tolerance range specifies the amount of deviation a part can possess and still be acceptable and function well within an assembly.

Different manufacturing fields use a different tolerance ranges. Where ±0.031 in. (0.79 mm) can be unacceptable in die work, the same tolerance range is too tight for, let us say, in steel constructions.

For comparison, quite precise tolerances for glass cutting are:

x.xxx	±0.015 in.	x.xx	±0.031 in.	fractions	±0.062 in.
x.xx	±0.40 mm	x.x	±0.80 mm	x	±1.5 mm

Minimal tolerances in woodworking, where NC equipment is utilized, are approximately:

x.xxx	±0.062 in.	x.xx	±0.125 in.	fractions	±0.25 in. and more
x.xx	±1.5 mm	x.x	±3.2 mm	x	±6.5 mm

Every manufacturing field adjusts the tolerance ranges to suit its needs. The fits, however, are a rather different story, as they always involve two parts, assembled together. Here the tolerance range must be somewhat standardized and often quite precise. After all, we are not fitting wooden shafts into openings drilled through glass.

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4-1-1 Types of Fits in Assembly of Parts

The inch-based measuring system has one great advantage—it may establish several layers of dimensions for easy application of tolerances. In die design, we most often have:

x.xxx	±0.005 in.
x.xx	±0.010 in.
x.x	±0.015 in.
Fractions	±0.031 in.

which translates into metric system's three layers only roughly, as follows:

x.xx	±0.13 mm
x.x	±0.25 mm
x	±0.40 mm

These tolerance ranges are rather common in metal fabricating field.

The general range of tolerances, as published by the American Standards Association in 1925 (ASA Standard B4a 1925) runs as shown in Table 4-1.

The use of this table is based on the hole dimension being the nominal size, toleranced on the plus side, with negative tolerance range equal to zero.

The shaft is handled in the opposite way, its tolerance ranges being negative, with plus tolerance equal to zero.

However, we will discuss the current American shop practice with regard to toleranc-ing, later in this chapter.

In *metric environment*, the basic representation (IT) of ISO tolerancing system comes in eighteen levels of accuracy. For levels IT 5 through IT 16, a simple formula can be used,

$$i = 0.45\sqrt[3]{D} + 0.001D \tag{4-1}$$

TABLE 4-1 Tolerance Ranges Per ASA Std. B4a-1925

Class of fit	Clearance	Interference	Hole tolerance	Shaft tolerance
1. Loose fit	$0.0025\sqrt[3]{D^2}$		$+0.0025\sqrt[3]{D}$	$-0.0025\sqrt[3]{D}$
2. Free fit	$0.0014\sqrt[3]{D^2}$		$+0.0013\sqrt[3]{D}$	$-0.0013\sqrt[3]{D}$
3. Medium fit	$0.0009\sqrt[3]{D^2}$		$+0.0008\sqrt[3]{D}$	$-0.0008\sqrt[3]{D}$
4. Snug fit	0.0000		$+0.0006\sqrt[3]{D}$	$-0.0004\sqrt[3]{D}$
5. Wringing		0.0000	$+0.0006\sqrt[3]{D}$	$+0.0004\sqrt[3]{D}$
6. Tight		$0.00025D$	$+0.0006\sqrt[3]{D}$	$+0.0006\sqrt[3]{D}$
7. Medium force		$0.0005D$	$+0.0006\sqrt[3]{D}$	$+0.0006\sqrt[3]{D}$
8. Heavy force		$0.001D$	$+0.0006\sqrt[3]{D}$	$+0.0006\sqrt[3]{D}$

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where D is the geometric center with respect to all combined tolerance ranges, in. or mm and i is the unit of tolerance, in micrometers (μm).

The upper allowable deviation is described as *es* or *ES*. This is the difference between the given basic diameter and its maximum deviation from this number. The lower deviation is *ei* or *EI*, and it is the difference between the basic diameter and the lower tolerance range.

Both these abbreviations are taken from French, where *es*/*ES* is described as *écart superieur* and *ei*/*EI* is *écart inferieur*.

The relationship between the two variations applies as follows. Notice the differentiation between shafts and holes by assigning capital letters to the latter.

For shafts $\quad ei = es - IT$

$\quad es = ei + IT$

For holes $\quad ES = EI + IT$

$\quad EI = ES - IT$

where IT is the basic tolerance range. Selected IT values are given in Table 4-2.

Every punch or die, or any other shape of an object to be mounted per specific requirements, is considered a *shaft* in this description. The same way, every opening of any shape is considered a *hole*.

The dimensional variations described above are used as alphabetically/numerically coded. These values are applied to the holes and shafts in the following manner:

For shafts, $\quad a$ through h = upper tolerance range, es

$\quad j$ through z = lower tolerance range, ei

For holes, $\quad A$ through H = lower tolerance range, EI

$\quad J$ through Z = upper tolerance range, ES

Tolerance ranges A & a and Z & z present the widest differences of the whole arrangement. They vary the most from the zero-middle line and this way they allow for the loosest fits. The closer to the zero line, the tighter the dimensional tolerances become. The zero value of tolerance ranges can be observed with J & j denominations, where their deviations in either direction are equal and therefore they cancel each other out.

Some recommended shaft/hole variations are presented in Table 4-3. Table 4-4 depicts the actual values of selected tolerance ranges.

TABLE 4-2 Selected Basic Tolerance Range (IT) Values (Metric)

Dimension range (mm)		Basic tolerance range in micrometers (μm) Levels of accuracy				
From	To	1	2	3	4	5
3	6	1	1.5	2.5	4	5
6	10	1	1.5	2.5	4	6
10	18	1.2	2	3	5	8
18	30	1.5	2.5	4	6	9
30	50	1.5	2.5	4	7	11

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TABLE 4-3 Some Generally Recommended Metric Tolerance Ranges for Shafts and Openings

Shaft			Opening						
h6	D8	E8	F8	G7	H7	J7	K7	M7	N7
h7					H8	J8	K8	M8	N8
h8	D9	E8	F9–F8		H8				
h9	D10–D9	E8	F9–F8		H9–H8				
h11	D11				H11				
Opening			**Shaft**						
H6			f6	g5	h5	j5	k5	m5	n5
H7	d8	e8	f7	g6	h6	j6	k6	m6	n6
H8	d10–d9	e9	f9–f8		h9–h7	j7	k7	m7	n7
H10					h10–h9				
H11	d11				h11				

TABLE 4-4 Selected Basic Tolerance Deviations (Metric)

Shaft (mm)		Upper deviation, es (micrometers)					
From	To	*d*	*e*	*f*	*g*	*h*	*j*
3	6	−30	−20	−10	−4	0	±IT/2
6	10	−40	−25	−13	−5	0	±IT/2
10	18	−50	−32	−16	−6	0	±IT/2
18	30	−65	−40	−20	−7	0	±IT/2
30	50	−80	−50	−25	−9	0	±IT/2

Opening (mm)		Lower deviation, EI (micrometers)						Upper deviation, ES (micrometers)
From	To	*D*	*E*	*F*	*G*	*H*	*J*	*J*
3	6	+30	+20	+10	+4	0	±IT/2	+5 to +10
6	10	+40	+25	+13	+5	0	±IT/2	+5 to +12
10	18	+50	+32	+16	+6	0	±IT/2	+6 to +15
18	30	+65	+40	+20	+7	0	±IT/2	+8 to +20
30	50	+80	+50	+25	+9	0	±IT/2	+10 to +24

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4-2 DIE COMPONENTS, THEIR FABRICATION, AND ASSEMBLY

A die, as mounted in the press, is a complex-action mechanism, producing parts in predetermined sequence. The lower half of the die, mounted on the lower die shoe, is firmly attached to the press bed, while the upper portion is bolted to the ram, sliding up and down along with it.

Aside from an upper and lower die shoe, every die consists of several other blocks, which hold or support the punches, dies, bushings, inserts, and other elements.

The die in Fig. 4-1 has several piercing punches with the last punch being the blanking station. All punches are assembled into a block called a *punch plate*, which is separated from the upper die shoe by a backup plate. Backup plates protect the die shoe from the effect of forces generated during the operation of the die. These plates are made of hardened steel, usually $^3/_8$ in. (10 mm) thick, with a $^1/_2$ in. (15 mm) exception for heavy work.

The stripper, shown in Fig. 4-1, is stationary, meaning that it does not ride along with the upper half of the die, instead it is firmly attached to the die block. Usually a milled channel for guidance of the metal strip is produced in its bottom surface for that purpose.

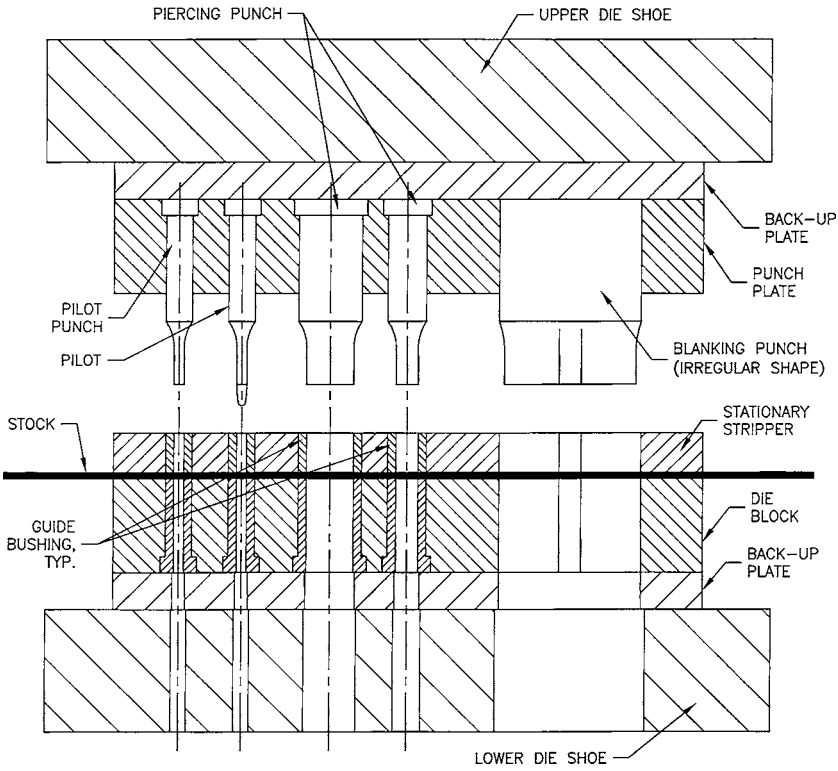

FIGURE 4-1 Progressive die.

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A stripper prevents the piercings from sticking to punches. It also restrains the rest of the strip from moving along with the upper half of the die by keeping it positioned on the face of a die block.

The die block contains all bushings, forming dies, or cutting inserts. It is supported by another backup plate positioned between this block and the lower die shoe.

All cutting, forming, and other material-altering punches and dies are assembled into their respective blocks using two methods of attachment: Either their body diameter D is press-fit within the block, with their heads remaining loose, or their head diameter is press-fitted, while the body remains loose.

As it often happens with progressive dies, there is not much that can be ascertained just by looking at the two opened halves of the tool. Only on scrutinizing the strip or strip layout, by comparing it to the cross-section of the die, and by studying details of punches and bushings, we can discover what this tool is really doing and how it is producing producing high-quality, close-toleranced parts each time the ram of the press slides down.

Majority of such work is done by components of the die, which are punches, die buttons, forming blocks, cutoff shears, special arrangements, and others. The die blocks, die shoes, strippers, pressure pads and similar, are but supportive elements, which contain, guide, or protect the active segments of the assembly. Naturally, the alignment of these components is of crucial importance. And so is their location within the die sequence, their precision fit, perpendicularity, type of steel and hardness, surface finish, to name but a few influential factors.

A few pointers on the fabrication and assembly of die components are added below.

4-2-1 Punches

Punches and dies are the most basic components of every die. Their bodies and shapes can be Electro Discharge Machined (EDM'd) from a block or blank, or from a bar stock or other materials. The material these tooling elements are made from is of a great importance, not only for its hardness and ductility, but for its behavior in production, resistance to galling, resistance to changes in material structure due to heat, frequency of sharpening, and the like.

Every punch and die, when assembled together, must fit exactly; there is no allowance for a slight shift here or there. With a small misalignment, great differences in punch and die clearances can be generated, which, given the time, will certainly exert a detrimental effect on the whole die, not talking about quantities of less-than-perfect parts such a tool can produce. We should bear in mind that dies are but small, automated production systems. As such, dies are capable of producing numerous perfect parts per hour. But at the same rate, they can produce rejects, should something within their design, construction, or assembly go wrong.

A sample of a typical punch, its dimensioning and tolerances is shown in Fig. 4-2. Notice the diameter of the cutting portion P is quite precise. *This dimension is always that of the opening to be pierced*. The cutting tolerance is added to the die opening.

Mounting of punches is evaluated in Fig. 4-3 with respect to the two mounting techniques already described: Either the shank is press-fit within the block while the head is loosely contained in the counterbore (Fig. 4-3*a*), or the head is press fit and the shank is loose (Fig. 4-3*b*). The second method of mounting is reserved for special instances, whereas the first method is commonly used for mounting of majority punches.

The proper length of a punch has a considerable effect on the overall performance of the die. With too long punches, the compressive stress on them may be excessive, resulting in

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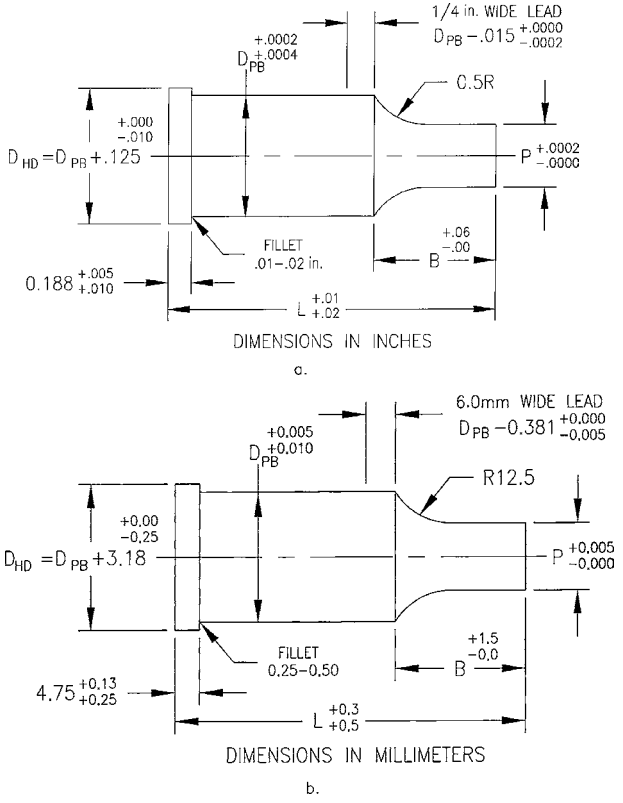

FIGURE 4-2 Detail of a punch.

frequent breakages. The maximum length of a punch may be calculated with the aid of the formula

$$L = \frac{\pi d}{8}\sqrt{\frac{Ed}{St}} \tag{4-2}$$

where L = maximum length of the punch
d = punch diameter
t = thickness of punched material
E = modulus of elasticity
S = shear stress of the material

The ratio of the punch diameter to the stock thickness must satisfy the condition

$$\frac{d}{t} = 1.10 \text{ minimum}$$

Smaller ratios are generally not recommended in sheet-metal practice, not that smaller holes cannot be produced, but their method of manufacture is much more complicated.

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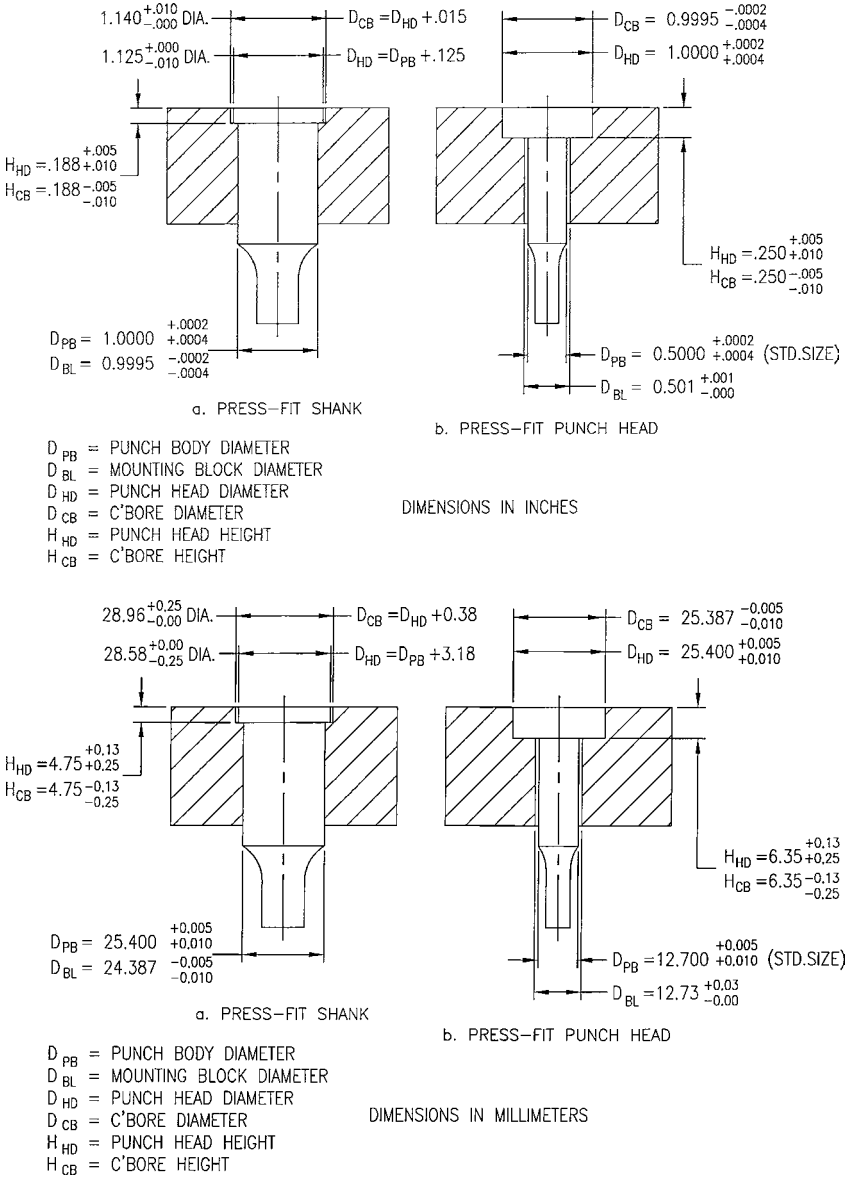
1.140 +.010 −.000 DIA.
1.125 +.000 −.010 DIA.
D_CB = D_HD +.015
D_HD = D_PB +.125
H_HD = .188 +.005 +.010
H_CB = .188 −.005 −.010
D_PB = 1.0000 +.0002 +.0004
D_BL = 0.9995 −.0002 −.0004
a. PRESS–FIT SHANK
D_CB = 0.9995 −.0002 −.0004
D_HD = 1.0000 +.0002 +.0004
H_HD = .250 +.005 +.010
H_CB = .250 −.005 −.010
D_PB = 0.5000 +.0002 +.0004 (STD.SIZE)
D_BL = 0.501 +.001 −.000
b. PRESS–FIT PUNCH HEAD
D_PB = PUNCH BODY DIAMETER
D_BL = MOUNTING BLOCK DIAMETER
D_HD = PUNCH HEAD DIAMETER
D_CB = C'BORE DIAMETER
H_HD = PUNCH HEAD HEIGHT
H_CB = C'BORE HEIGHT
DIMENSIONS IN INCHES
28.96 +0.25 −0.00 DIA.
28.58 +0.00 −0.25 DIA.
D_CB = D_HD +0.38
D_HD = D_PB +3.18
H_HD = 4.75 +0.13 +0.25
H_CB = 4.75 −0.13 −0.25
D_PB = 25.400 +0.005 +0.010
D_BL = 24.387 −0.005 −0.010
a. PRESS–FIT SHANK
D_CB = 25.387 −0.005 −0.010
D_HD = 25.400 +0.005 +0.010
H_HD = 6.35 +0.13 +0.25
H_CB = 6.35 −0.13 −0.25
D_PB = 12.700 +0.005 +0.010 (STD.SIZE)
D_BL = 12.73 +0.03 −0.00
b. PRESS–FIT PUNCH HEAD
D_PB = PUNCH BODY DIAMETER
D_BL = MOUNTING BLOCK DIAMETER
D_HD = PUNCH HEAD DIAMETER
D_CB = C'BORE DIAMETER
H_HD = PUNCH HEAD HEIGHT
H_CB = C'BORE HEIGHT
DIMENSIONS IN MILLIMETERS

FIGURE 4-3 Mounting of punches.

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Better punch materials with higher compressive strengths may be required, and additional stripping and tool-guiding arrangements may be needed, along with greater clearances between the punch and die.

Other restrictive conditions, dealing with similar situations, may be followed up in Sec. 6-8.

When assembling the punch into a punch plate, or the die into the die block, a certain tightness of fits is mandatory. After all, the punch cannot jump up and down in the opening with every stroke of a press. The tightness, or rather interference between the tool shank and its opening, is called *press fit* and in American shops it follows specific guidelines, where the maximum amount of interference between any two objects is to be 0.0014 in. (0.035 mm). Interferences greater than that will not allow for the assembly of parts.

Sometimes, the extremes have to be resorted to, such as heating the block and freezing the punch, as the punch is always slightly larger than the opening. Pushing the punch or die into an opening with a small press is another method of assembly.

With 0.014 in. (0.035 mm) *total indicator reading* (T.I.R.), die components will succumb to the harsh assembly conditions and will be well-seated in their respectable openings. With respect to the above, the punch body diameter, including its highest amount of tolerance (see Fig. 4-3*a*) will be

$$1.0000 + 0.0004 = 1.0004 \text{ in.}$$
$$(25.400 + 0.010 = 25.410 \text{ mm})$$

The punch plate opening into which the punch will be assembled (here we subtract the higher of the two tolerance amounts) is

$$0.9995 - 0.0004 = 0.9991 \text{ in.}$$
$$(25.387 - 0.010 = 25.377 \text{ mm})$$

The total variation between these two numbers is

$$1.0004 - 0.9991 = 0.0013 \text{ in.}$$
$$(25.410 - 25.377 = 0.033 \text{ mm})$$

Note: The metric dimensional discrepancy between the recommended variation of 0.035 mm and the calculated variation of 0.033 mm is due to rounding of converted numerical values.

This interference is acceptable, and yet the ranges of tolerance for the two vital dimensions are not out of the ordinary. Through such evaluation we may assess that if the two parts were to be made to the fullest extent of their tolerance ranges, they still could be press-fit together.

Now the lower amount of press-fit scenario has to be assessed, where the minimum amount of interference between two press-fit objects is 0.0003 in. (0.008 mm). This lower end of the tolerance range should be evaluated as well, to provide for a situation where both parts may be made to their smallest possible press-fit dimensions.

The punch size, including the lower value of the two tolerance ranges, will be

$$1.000 + 0.0002 = 1.0002 \text{ in.}$$
$$(25.400 + 0.005 = 25.405 \text{ mm})$$

The punch plate opening minus the smaller amount of tolerance is

$$0.9995 - 0.0002 = 0.9993 \text{ in.}$$
$$(25.387 - 0.005 = 25.382 \text{ mm})$$

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Subsequently,

$$1.0002 - 0.9993 = 0.0009 \text{ in.}$$

$$(25.405 - 25.382 = 0.023 \text{ mm})$$

0.0009 in. (0.023 mm) is quite a tight fit, which clearly indicates that the assembly will be adequately stable. But the absolute minimum of interference, such as that where no tolerance buildup of any kind will be generated on either of the two parts, must be judged as well. This condition is obtained by comparing the two basic dimensions as follows:

$$1.0000 - 0.9995 = 0.0005 \text{ in.}$$

$$(25.400 - 25.387 = 0.013 \text{ mm})$$

With 0.0005 in. (0.013 mm) being the lowest possible interference and 0.0013 in. (0.033 mm) being the highest, we have an acceptable level of press fit for the two metal parts. However, dimensions of actual products are rarely found on either extreme side of their tolerance range but are rather somewhere in between. Therefore, it is not important in which section of the tolerance range these parts are made. As long as they are made within the drawing's dimensional requirements, they will fit.

The second method of assembly, shown in Fig. 4-3*b*, should be evaluated the same way. Here we control the tolerance buildup of the press-fitted punch head. Its size and tolerances were purposely made the same so that the equality of both methods can be easily demonstrated.

The height of the punch head in this type of assembly is usually greater, since the increased length of the press-fit area is vital to the stability of the tool.

In assembly, the process of inserting punches and dies into their openings in blocks is aided by the presence of a lead. The lead is a $^1/_4$ in. wide band on the circumference of the punch shank (or die), which is slightly smaller in diameter, for an easy entry of the large part into the smaller, press-fit opening.

4-2-1-1 Depth of the Counterbore Versus the Height of the Punch Head. When comparing the thickness of the punch head to the depth of the counterbored opening, it is obvious that the metal of the punch head is purposely being allowed to exceed the height of the block. This is because after all punches are assembled, the whole block is placed into the surface grinder, where all punch heads are leveled down so that they will be flushed with the block.

Tolerance ranges for the height of punch head lean toward the plus side, while tolerances for the depth of counterbore go in the minus direction.

The height of the punch head in Fig. 4-3*a*, is dimensioned as

$$0.188 \begin{matrix} +0.005 \\ +0.010 \end{matrix} \text{ in.}$$

$$\left(4.75 \begin{matrix} +0.13 \\ +0.25 \end{matrix} \text{ mm}\right)$$

Note: Some values converted to metric are purposely rounded to the nearest 5 or 10, to comply with the European dimensioning customs.

It can be minimally 0.188 in. (4.75 mm), with its maximum size being 0.198 in. (5.0 mm). The two tolerance ranges being in the same direction (both plus) indicates that such a dimension should never slip into the opposite, into minus.

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The counterbore's depth begins with the same nominal dimension, toleranced on the minus side:

$$0.188\ ^{-0.005}_{-0.010}\ \text{in.}$$

$$\left(4.75\ ^{-0.13}_{-0.25}\ \text{mm}\right)$$

Here the opening's depth can be a maximum of 0.188 in. (4.75 mm), with its minimal size 0.178 in. (4.50 mm).

The total tolerance buildup between the two parts can be figured out by comparing their two most extreme dimensions:

$$0.198 - 0.178 = 0.020 \text{ in.}$$
$$(5.00 - 4.50 = 0.50 \text{ mm})$$

which means that the maximum difference between the height of the punch and the depth of the pocket can be 0.020 in. (0.51 mm). The minimal difference will be zero, since both start with the same nominal size, 0.188 in. (4.75 mm).

Another depth-tolerancing method uses slightly tighter tolerance ranges for both the punch head and its counterbore, with the offset between their basic dimensions. In such a case, the height of the punch head is

$$0.188\ ^{+0.005}_{-0.000}\ \text{in.}$$

$$\left(4.75\ ^{+0.13}_{-0.00}\ \text{mm}\right)$$

while the depth of the counterbore is automatically lowered some 0.005 in. (0.13 mm) or 0.010 in. (0.25 mm) (the exact amount depends on the manufacturing practice of the particular shop). The depth of counterbored pocket then becomes

$$0.178\ ^{+0.000}_{-0.005}\ \text{in.}$$

$$\left(4.50\ ^{+0.00}_{-0.13}\ \text{mm}\right)$$

The total tolerance buildup, obtained through comparison of the two most extreme sizes, will come out as

$$0.193 - 0.173 = 0.020 \text{ in.}$$
$$(4.88 - 4.37 = 0.51 \text{ mm})$$

The second punch head, shown in Fig. 4-3*b*, is dimensioned and toleranced similarly. Its tolerance range has already been tightened.

4-2-1-2 Jektole® Punches. Jektole punches are constructed similarly to regular punches, the difference being a spring-loaded, slug-ejecting pin in their center, as shown in Fig. 4-4. The pin, continuously forced out by the spring pressure, retreats back into the punch only on contact with the material during presswork. But as soon as the press-force is released, the pin springs out, forcing the slug off the punch face.

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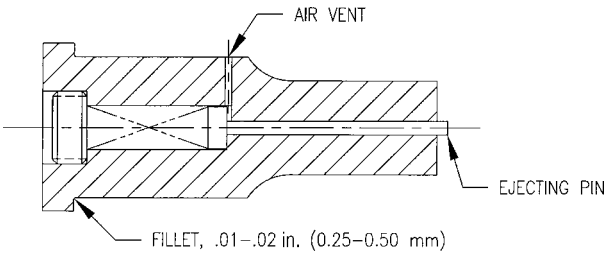

FIGURE 4-4 Jektole® punch. (*Technical illustration is reprinted with permission from Dayton Progress Corp., Dayton, OH.*)

According to the manufacturer, Jektole can use larger tolerance ranges between punches and dies. Where regular clearances of 5 to 8 percent per side produce holes undersized by –0.0002 to –0.0005 in. [0.005 – 0.013 mm], Jektole at 10 to 12 percent clearance per side produce cutouts on the plus side, or +0.0002 to +0.0005 in. [0.005 – 0.013 mm]. Such a generous clearance between the punch and die opening affects positively the amount of wear and tear of the cutting punch, for which reason Jektole punches were found producing three times more cuts than punches with regular clearance. Additionally, the following results were observed:

- Greater rollover surface, while the burnished surface is diminished. The resulting reduction of compressive stresses is outbalanced by an increase in tensile stresses, which are needed for the procurement of a cut. The result can be seen in diminished need for sharpening of tooling, reduced breakage, and reduced downtime.
- Lesser bulging of the cut material (see Fig. 4-5). A bulge in the material, where produced, tightens around the punch and prevents its withdrawal to the point of breaking it, if either tooling clearance or punch diameter is too small. Jektole punches do not suffer from such an effect, which is why the wear of punches is reduced to merely one-third of normal-clearance wear.
- Less friction between the Jektole punch and the material produces less heat, while diminishing the abrasion effect.

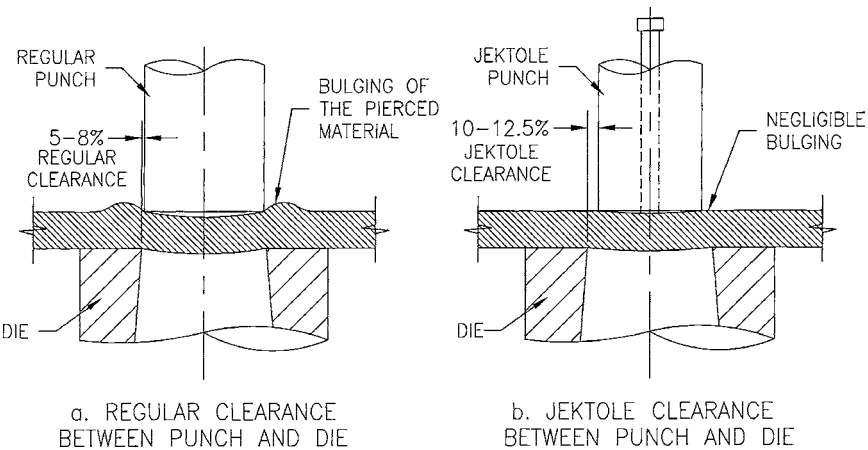

FIGURE 4-5 Comparison of clearances: regular punch and Jektole®. (*Technical illustration is reprinted with permission from Dayton Progress Corp., Dayton, OH.*)

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- Smaller burr than that created by a 5 percent clearance-per-side tooling.
- 0.0005 to 0.002 in. [0.013 to 0.051 mm] clearance per side for shaving operations.

Additionally, slug-pulling problems, when the slugs are dragged to the die surface by the retracting punch, were alleviated.

4-2-1-3 Quill Punches. Quill punches (Fig. 4-6*c* and *d*) are used for close-spaced openings or cluster tooling. Their heads are quite small, which is the reason why they easily fit into congested areas. Because of their small body diameter, they are quite fragile; often a majority of their length has to be contained in a bushing, which not only supports their mass, but also serves as a guide. When guided, quills can withstand much more stress and strain.

To further support quill's performance, a guided stripper plate is recommended in technical literature. A sample of a guided stripper plate is shown in Fig. 4-7.

4-2-1-4 Work Stresses and Their Impact on the Punches. Punches and dies in production are exposed to various types of harmful influences, be it stresses from the work

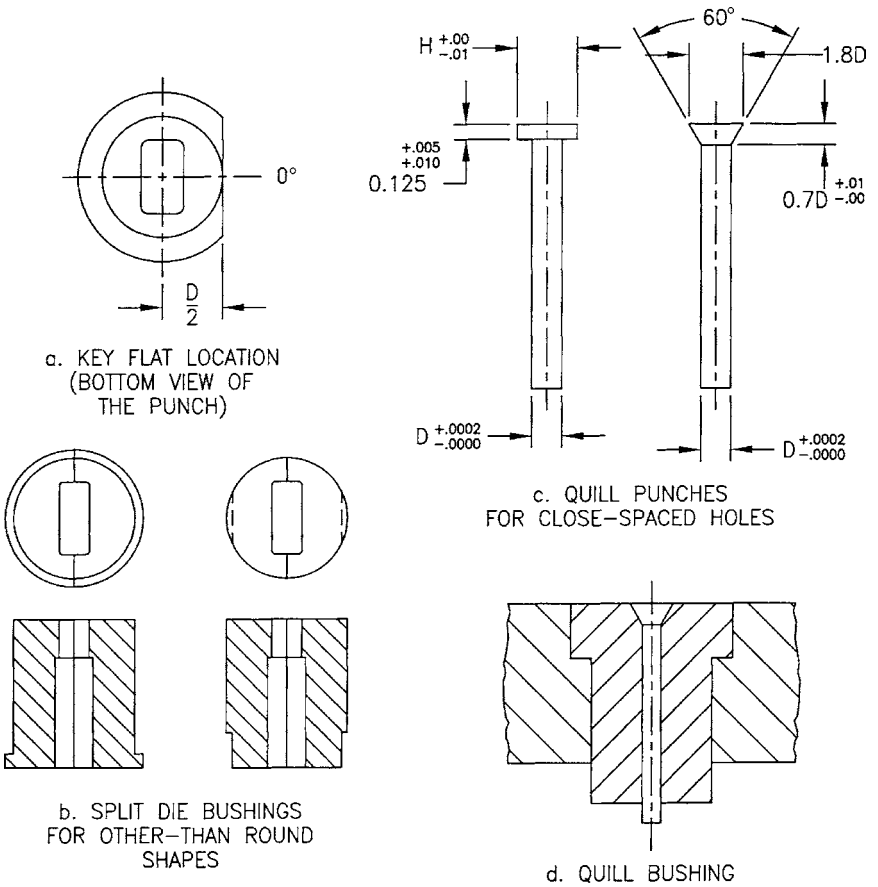

FIGURE 4-6 Miscellaneous punches and dies (dimensions in inches).

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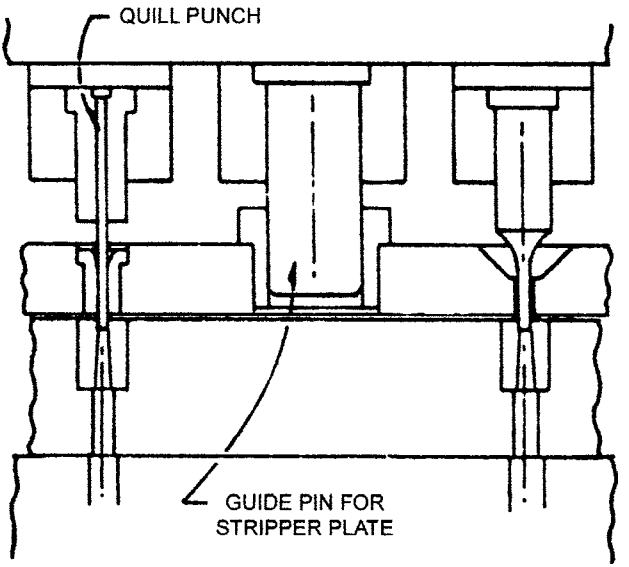

FIGURE 4-7 Guided assembly with quills. (From: *Practical Aids For Experienced Die Engineer, 1980. Reprinted with permission from Arntech Publishers, Jeffersontown, KY.*)

itself, stresses created by friction, or stresses from compressive loading and impact loading. Stresses caused by impact loading can make a slender punch body quiver, which predisposes it to deflection or even buckling. From such, a permanent misalignment may result. Where too loose a clearance opening in the stripper pad is counted on to guide the punch (see Fig. 4-8*b*), the distortion due to punch vibration can progress unrestricted and eventually breakage of the punch will result.

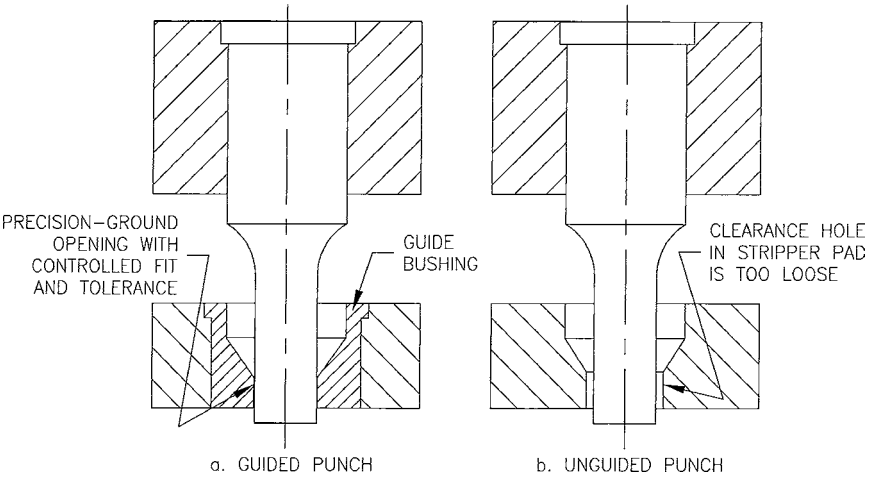

FIGURE 4-8 Guided and unguided punch.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

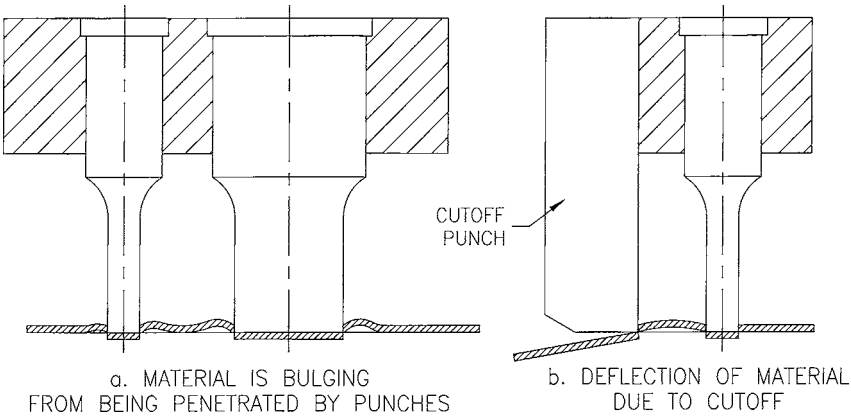

FIGURE 4-9 Distortion in sheet-metal material due to congested cutting. (*Technical illustration is reprinted with permission from Dayton Progress Corp., Dayton, OH.*)

Generally, punches of smaller diameters should be guided on their way through the stripper, for which reason guide bushings are utilized (see Fig. 4-8*a*). These bushings not only guide the punch, they are also enforcing its proper alignment, providing support where and when needed and this way they are protecting the punches from excessive damage and breakage.

Guide bushings are also recommended where crowding of punches and dies is encountered. In such a situation, a heavy cutting action alongside a slender punch can send a wave of cut-stressed material against its body (see Fig. 4-9*a*), with resulting breakage soon afterwards. Staggered cutting can help in this scenario.

Another harmful influence can be created by the deflection of material in shear or cutoff operation, as shown in Fig. 4-9*b*. Here the pressure of bulging material may attack the body of the punch and cause damage over the time.

Additional force acting upon the punch during each press stroke is the compressive force. Sometimes, this force may be of such a magnitude that the punch mass cannot compensate for it and a breakage occurs. Usually, the head of the punch snaps off, with the breakage line starting where the head joins the body diameter (see Fig. 4-10). When this happens, we have a choice of several possibilities to investigate (see Fig. 4-11).

Other solutions include the head thickness increase for greater mass of the affected area. Similarly, the punch body diameter may be enlarged for greater sturdiness. Changes to the punch face configuration may be of help, especially where a greater punch diameter is concerned. A shear to the cutting surface, allowing the punch to enter the pierced material gradually, may be beneficial (see Fig. 4-12).

The backup plate, where used, should be made of A2 steel, hardened to 40 to 50 HRc. Oil-hardened steel should be avoided, as the heat treatment causes a greater amount of warpage in it, which in turn produces inconsistencies in the plate's flatness. Where the backup plate is too hard, vibrations may develop in response to the press function, ruining the punch over time.

4-2-2 Die Button or Die Bushing

Die button, or *die bushing* is shown in Fig. 4-13 in several variations. The first, *a* version, is used and dimensioned for piercing of a single opening, while the *b* style may produce the

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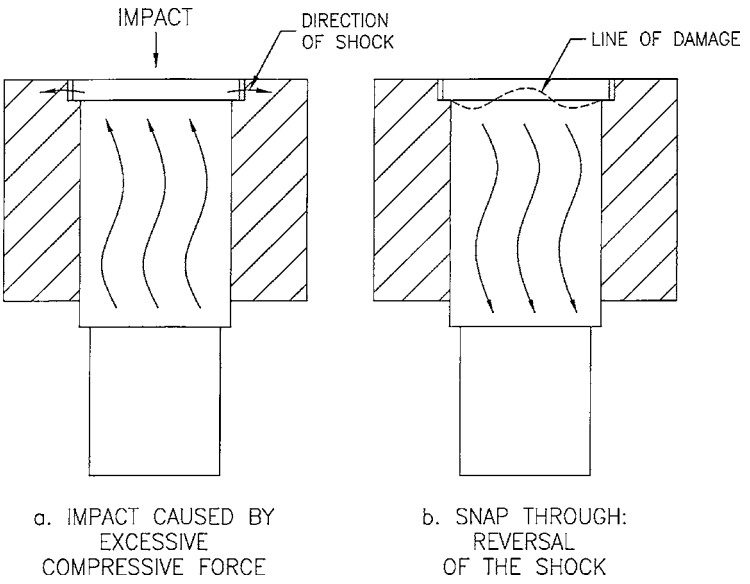
IMPACT
DIRECTION OF SHOCK
LINE OF DAMAGE
a. IMPACT CAUSED BY EXCESSIVE COMPRESSIVE FORCE
b. SNAP THROUGH: REVERSAL OF THE SHOCK

FIGURE 4-10 Head breakage in punches. (*Technical illustration is reprinted with permission from Dayton Progress Corp., Dayton, OH.*)

inner and outer diameter at the same time. The headless die button (Fig. 4-13*c*) is often used with a lighter type of work or with parts such as wave washers. The absence of the heel may reduce the cost of such a bushing's manufacture and assembly, but the disadvantage of such an unsecured press fit may be considerable.

Again, the tightness of manufacturing tolerance of the cutting surface may be observed. Two-tenths of an inch (0.0002 in. or 0.005 mm) variation from the nominal size can be viewed as precision work.

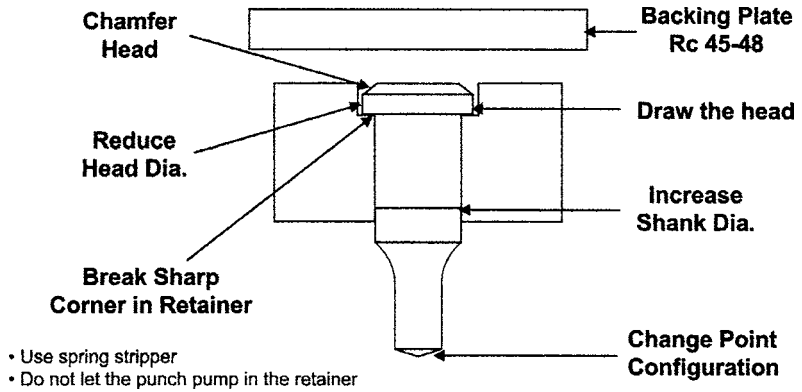
Chamfer Head
Backing Plate Rc 45-48
Draw the head
Reduce Head Dia.
Increase Shank Dia.
Break Sharp Corner in Retainer
Change Point Configuration
• Use spring stripper
• Do not let the punch pump in the retainer

FIGURE 4-11 Punch breakage solutions. (*Technical illustration is reprinted with permission from Dayton Progress Corp., Dayton, OH.*)

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

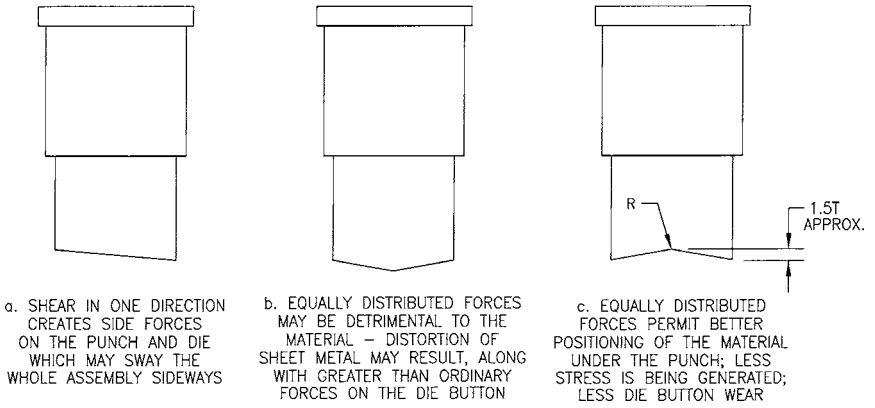
R
1.5T
APPROX.
a. SHEAR IN ONE DIRECTION CREATES SIDE FORCES ON THE PUNCH AND DIE WHICH MAY SWAY THE WHOLE ASSEMBLY SIDEWAYS
b. EQUALLY DISTRIBUTED FORCES MAY BE DETRIMENTAL TO THE MATERIAL – DISTORTION OF SHEET METAL MAY RESULT, ALONG WITH GREATER THAN ORDINARY FORCES ON THE DIE BUTTON
c. EQUALLY DISTRIBUTED FORCES PERMIT BETTER POSITIONING OF THE MATERIAL UNDER THE PUNCH; LESS STRESS IS BEING GENERATED; LESS DIE BUTTON WEAR

FIGURE 4-12 Shear of the punch face.

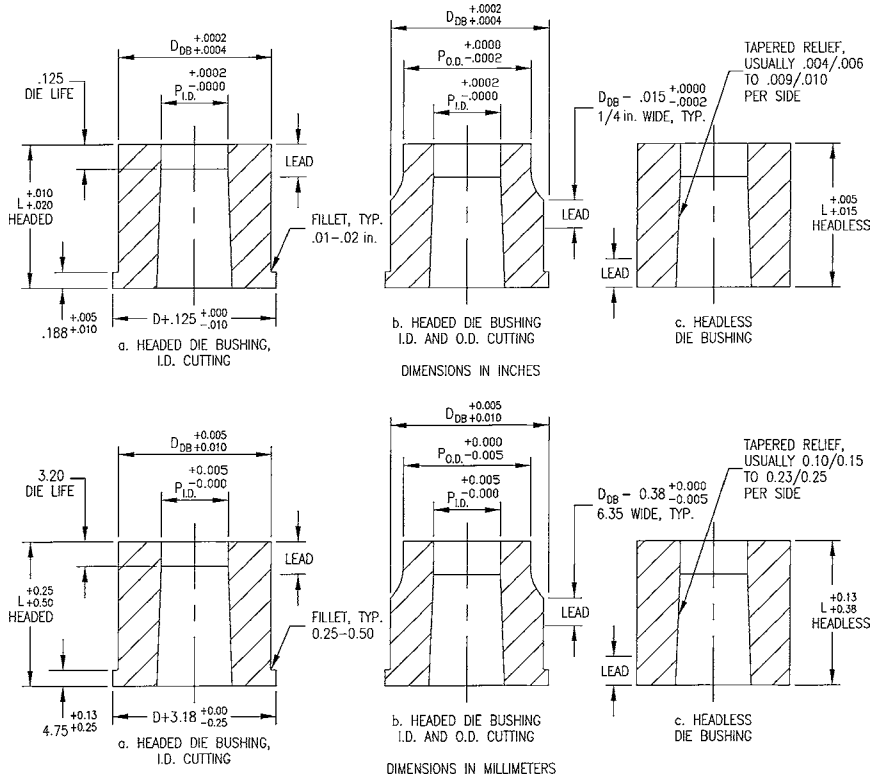

FIGURE 4-13 Die button.

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Every die bushing has an opening into which a punch slides when cutting the sheet-metal material. Such an opening is absolutely straight and precisely finished. It is called the "die life" (or "land"), and it is the amount of the die height which can be used up for subsequent sharpenings. The height of the die life depends on the number of pieces the die has to produce and on the number of expected sharpenings during the die button's existence in the die.

The height of this area is a debatable subject. In order to prolong the life of a die, a considerable die-life size may be chosen, which may be expected to provide for many sharpenings afterward. But, if such a tight portion is excessively long, the piercings, leaving the die through this channel, may get packed there, perhaps unable to move forward. Such a condition may endanger not only the punch and die but the whole die assembly as well.

Usually a $^1/_8$ in. (3.2 mm) length of die life is specified; rarely a greater size can be found.

At the other end of the die life the opening enlarges, turning into a clearance hole, through which the slugs leave the die. Usually this enlargement has a form of draft, most often in the vicinity of 1.5 to 2° taper.

4-2-2-1 Slug Removal. The three types of slug relief are as shown in Fig. 4-14; a tapered and counterbored relief with a die life (also called "land"), and a relief that is tapered through with no die life. Each of these designs has its advantages and disadvantages. For example, the tapered relief controls the movement of flat slugs through the die, while the counterbored opening allows them to tumble and jam. The jamming of slugs, their spinning around, bridging against each other and sticking together, can have a detrimental effect on the quality of the pierced part and naturally, it is endangering the tooling as well.

The tapered die relief is more supportive to the cutting edge, and as such, this die often outlasts counterbored openings. Therefore, it may be summarized that most often, the improperly chosen or improperly produced slug-relief openings are the main causes of many slug-related problems.

Counterbored relief opening has its uses elsewhere. It can be successfully utilized to serve as a stripper, in situations where a cup is pushed past the die life right after being formed. On retrieval of the punch, the cup cannot follow, being prevented by the counterbore's pocket (see Fig. 4-15). Here the stripping capacity of the counterbored step in the die is further enhanced by the fact that the cup, or some portions of it, will certainly experience some springback and will try to increase its upper diameter.

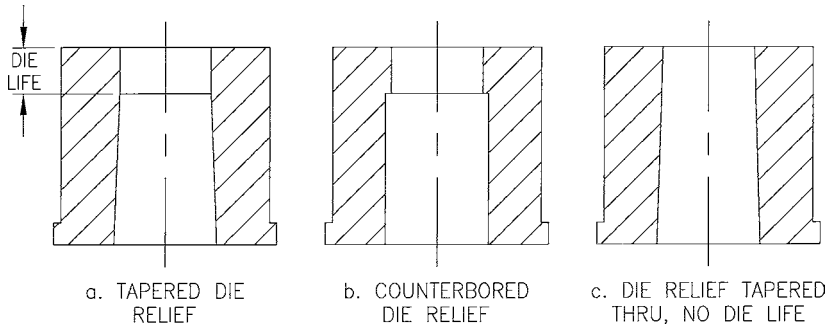

FIGURE 4-14 Three types of die relief.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

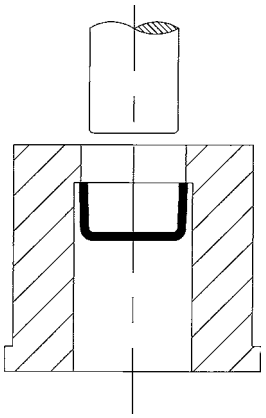

FIGURE 4-15 Counterbored die relief serving as a stripper.

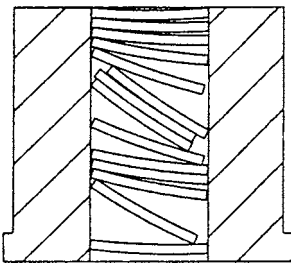

FIGURE 4-16 Packing and dislocation of slugs in a die.

Another problem in slug removal is often encountered where the slug becomes retained in the die cavity and does not progress on the way down. It is soon joined by additional slugs, with which it forms a tightly-packed stack that would not go down. Such column of piercings can naturally damage the punch and sometimes even split the die button. To eliminate this problem, shortening the die life for piercing of thinner materials and evaluating the punch-die clearance may help. Of advantage may be the use of *Jektole punch arrangement* described previously, which produces slugs slightly smaller than the die clearance, allowing them to fall through.

In situations where the die opening is not properly dimensioned and manufactured, the slugs can become packed tightly, with some of them even varying from the horizontal due to their uncontrolled movement through the die (see Fig. 4-16). Often such situations result in punch breakage, with die splitting possible as well.

4-2-2-2 Bazooka® Bushing. Another excellent method of slug-removal control is the *Bazooka sleeve*, also called *Bazooka bushing*. It is shown in Figs. 4-17 and 4-18. This slug-removing sleeve uses compressed shop air to create a vacuum, which is then applied at the die opening. The vacuum not only prevents slugs from sticking to the punch; it also forces them to follow the path of suction, afterwards being deposited in a container.

The vacuum system removal is more advantageous than that of removal of slugs with compressed air, for where compressed air can sometimes make the trimmings and slugs fly in the wrong direction, vacuum sleeve's controlled path of slug removal is precisely specified.

Bazooka vacuum sleeve can be installed directly into the die operating on a maximum air pressure of 60 psig. Sometimes the sleeve can be contained in a "funnel unit," as shown in Fig. 4-19. For more complex slug removal, a *vacuum transducer* and a *cap unit* are available (not shown).

4-2-3 Miscellaneous Notes

Keeping the die function at the optimal levels means not only taking care of all the punches and dies being properly fabricated and properly mounted. It also involves keeping detailed

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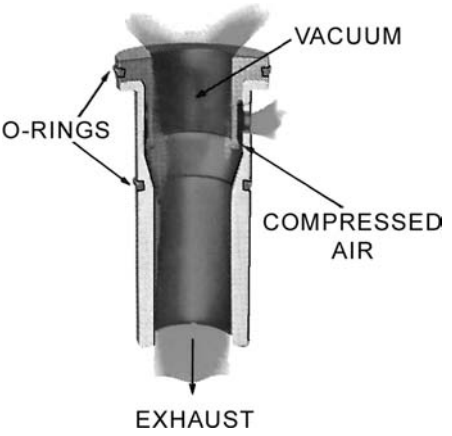

FIGURE 4-17 Bazooka® bushing. (*Reprinted with permission from Air-Vac Engineering Co., Seymour, CT.*)

methods of the die production, along with records of adjustments, sharpening records, information on lubricants used, and of course strip samples from at least the last run.

Few additional pointers, not included in the above text, are added here.

4-2-3-1 Variations of Punch and Die Cutting Diameter. As already mentioned, the cutting portion of the punch is always the size of the opening to be pierced. The opening in the die amounts to a total of the punch size, plus metal-cutting clearance.

Metal-cutting clearance is the difference between the size of the punch and that of the die. This term is not to be confused with the manufacturing tolerance, which in this case is +0.0002/–0.0000 in. (+0.005/–0.000 mm) for both punch diameter and die openings. Metal-cutting clearance is discussed in Sec. 6-5.

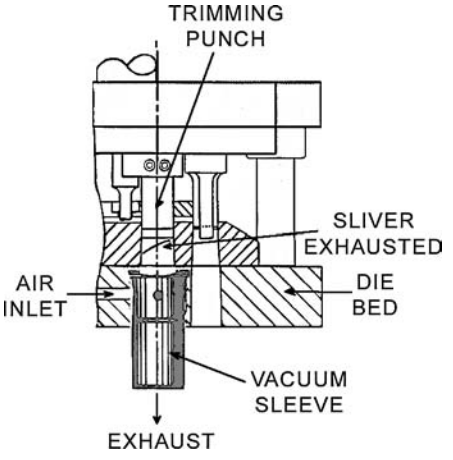

FIGURE 4-18 Bazooka® bushing as assembled in the die. (*Reprinted with permission from Air-Vac Engineering Co., Seymour, CT.*)

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

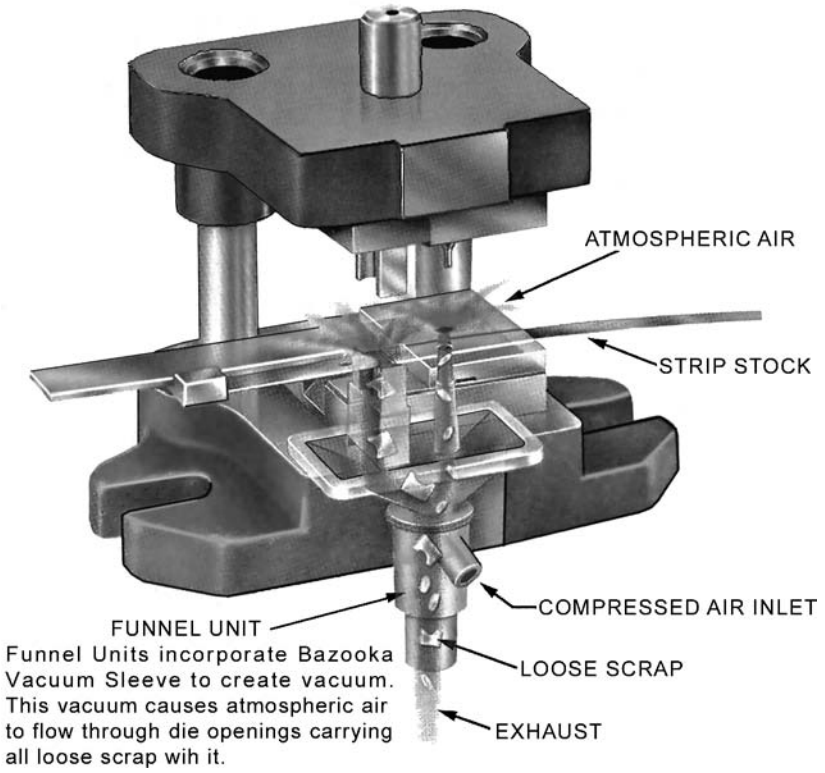
ATMOSPHERIC AIR
STRIP STOCK
COMPRESSED AIR INLET
FUNNEL UNIT
Funnel Units incorporate Bazooka Vacuum Sleeve to create vacuum. This vacuum causes atmospheric air to flow through die openings carrying all loose scrap wih it.
LOOSE SCRAP
EXHAUST

FIGURE 4-19 Bazooka® Funnel Unit with Bazooka® Vacuum Sleeve. (*Reprinted with permission from Air-Vac Engineering Co., Seymour, CT.*)

Therefore, the inside diameter of the die, or P_{ID}, will be

$$P_{ID} = (P_{punch} + \text{cutting clearance}) \begin{matrix} +0.0002 \\ -0.0000 \end{matrix} \text{ in.} \left(\text{or } \begin{matrix} +0.005 \\ -0.000 \end{matrix} \text{ mm} \right)$$

However, should a die be used to cut both diameters, inner and outer, such as the one shown in Figs. 4-20*b* and 4-58, its outer edge, that is, the second cutting edge (die), will take upon itself the function of a punch, with its corresponding die-bushing part being shifted into the punch-plate location. The outside dimension of the die, or P_{OD}, will then become the exact size of the opening to be punched, with the metal-cutting clearance added to its corresponding die member, held in the punch plate. A manufacturing tolerance of +0.0002/–0.0000 in. (+0.005/–0.000 mm) will then be assigned to such a punch. Its opposite die part would be dimensioned as

$$P_{die-pt} = (P_{OD} + \text{cutting clearance}) \begin{matrix} +0.0002 \\ -0.0000 \end{matrix} \text{ in.} \left(\text{or } \begin{matrix} +0.005 \\ -0.000 \end{matrix} \text{ mm} \right)$$

Mounting methods of guide bushings are similar to mounting methods for punches. Therefore, the earlier description of the procedure applies here too.

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The height of the bushing in Fig. 4-20*a* should be equal to the thickness of the die block; the bushing shown in Fig. 4-20*b* must be higher than the die block to allow for dual cutting.

4-2-3-2 Locating Methods for Punches and Dies. Other than round punches should be well aligned with their respective bushings and either part of the assembly should not rotate or otherwise deviate during the die function. This, along with the correctness of the initial installation, is assured by keying the punch or die's head and placing a standard keyway against its surface.

Key flat portions are obtained by grinding the punch head all the way toward the shank diameter, as shown in Fig. 4-21. Some punches may have a single key flat; others may have two. With headless bushings, an undercut may be produced to serve the same purpose (see 4-21*c*).

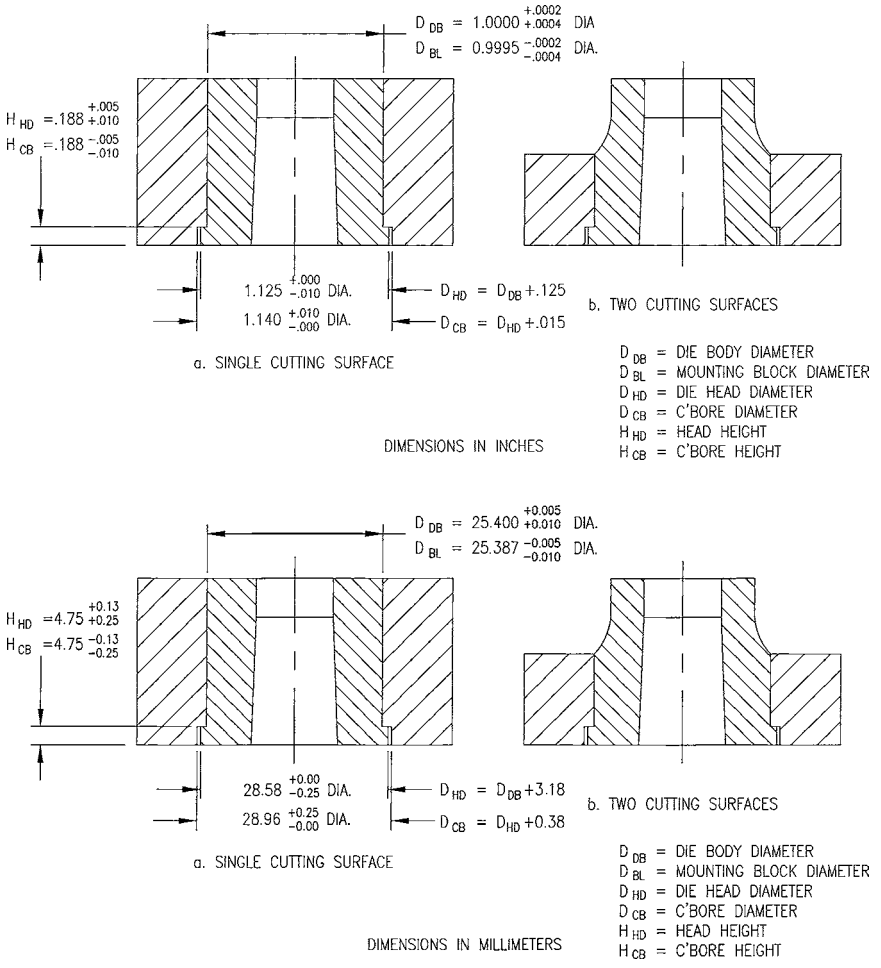

FIGURE 4-20 Mounting of a die.

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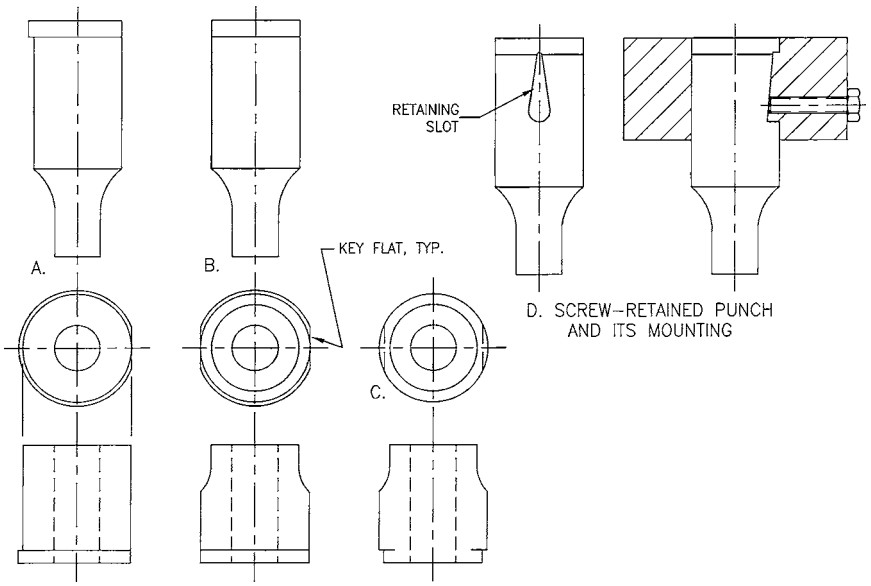

FIGURE 4-21 Locating methods for punches and dies.

Another locating feature is a retaining notch in the shank of a punch (Fig. 4-21*d*). A screw inserted through a side opening in the punch plate will secure the punch against rotational movement and against any vertical displacement.

The key flat portion is recommended to be used in congruence with the cutting shape of a punch, where it indicates its orientation, as shown in Fig. 4-6*a*.

Die bushings utilized for cutting of openings of various shapes may sometimes be cut in half to allow for easier manufacture and easier alignment during installation. (See Fig. 4-6*b*.) Lately, however, with the emergence of EDM-wire machinery, punches and dies of all shapes can be produced with a single cut, where the thickness of the wire already provides for the metal-cutting clearance.

4-2-3-3 Coating for Protection of Tooling. Coating of punches in protection of their surfaces against detrimental influences of the fabricated material and against the die work itself remains most often reserved to forming and drawing punches. Anyway, we would ask what protection would offer a coating to the face of a piercing punch, which has to be sharpened during service?

Yet, the experimental work* of Monika Gierzynska-Dolna, confirmed that punches for blanking of thin sheets gained from electro-spark hardening with tungsten carbides on the head and side surfaces. Punches for blanking of thicker materials were improved by either carbonitriding, or WC or Cr_2O_3 plasma. For dies, carbonitriding was recommended.

The film thickness should be in the vicinity of 40 to 200 μ-in. (i.e., 1 to 5 microns). Since this method of coatings' deposition does not affect the heat treatment hardness of the tooling material, it is safe to apply such coating to all applicable punches.

*Presented at the International Symposium of Metal Forming in Krakow (1987).

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For forming and drawing punches, the four most common types of coating protection are:

- Titanium Nitride (TiN), which protects the surface of the tool against abrasive and adhesive wear. The galling is diminished, which accounts for up to 200 percent increase in overall tool life.
- Titanium Carbonitride (TiCN) offers an excellent toughness, which is based on a closely interlocked grain structure. This type of coating improves wear resistance to abrasive, adhesive, or tacky and difficult-to-machine materials, such as aluminum alloys, copper alloys, tool steels, titanium alloys, and Inconel. An improvement to forming operations beyond that offered by TiN coating can be expected.
- Chromium Nitride (CrN) resists adhesive wear, corrosion, and oxidation. Recommended where titanium-based coatings were found inadequate. It works well with titanium and copper alloys.
- Titanium Aluminum Nitride (TiAlN) is a high-performance coating of improved ductility, resisting oxidation, and of unparalleled properties in heat resistance. Can be used for all abrasive, tacky, and difficult-to-machine materials, such as aluminum alloys, nickel alloys, and tool steels.

4-2-4 Pilots

In construction, pilots are similar to punches, with the only difference being in their smooth, radiused end (Fig. 4-22). In the die, pilots provide for a guidance of the strip by sliding into at least two pierced openings, located at the extreme edges of the sheet-metal strip, and positioning, or fine-adjusting the surrounding material around their bodies.

Pilots are always longer than any punches, to assure their contact with the strip prior to the occurrence of any cutting. Their diameter may be –0.003 in. (–0.08 mm) smaller than the diameter of the punch used for piercing pilot holes. Mounting of pilots utilizes the same procedure as that described for mounting of punches shown earlier in Fig. 4-3.

Pilot punches should always be as sturdy as possible. After all, these are first to engage the advancing sheet-metal strip and force it, where misfed, to conform to the positioning requirements. Headed, larger diameter pilots are therefore preferable.

For proper locating action, the flat portion of the pilot punch tip has to exceed the stripper surface to the tune of two material thicknesses, or $^1/_{16}$ in. (1.5 mm), whichever is greater (Fig. 4-23). As already preceded elsewhere in the text, the length of the pilot punch must be adequate to engage the pilot opening and locate the strip before any punching, forming, or any other die operation takes place.

The opening in the die block, which the pilot punch enters on its way down, does not have to be provided with a bushing. The size of the opening should be the pilot diameter plus a maximum of 0.25t per side.

Spring pilots (Fig. 4-24) do not need precision mounting holes and are therefore cheaper to install. Aside from providing for the guidance of a strip on some occassions, spring pilots may be used to support compression springs or to serve as lifting devices. The free end of the spring is usually contained in a simple pocket counterbored in the opposite plate. Obviously, these mounting arrangements are far from precise and as such, should not be used for accurate strip positioning.

The length of spring pilot tip should be equal to its diameter, plus $^1/_8$ in. (3.2 mm).

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

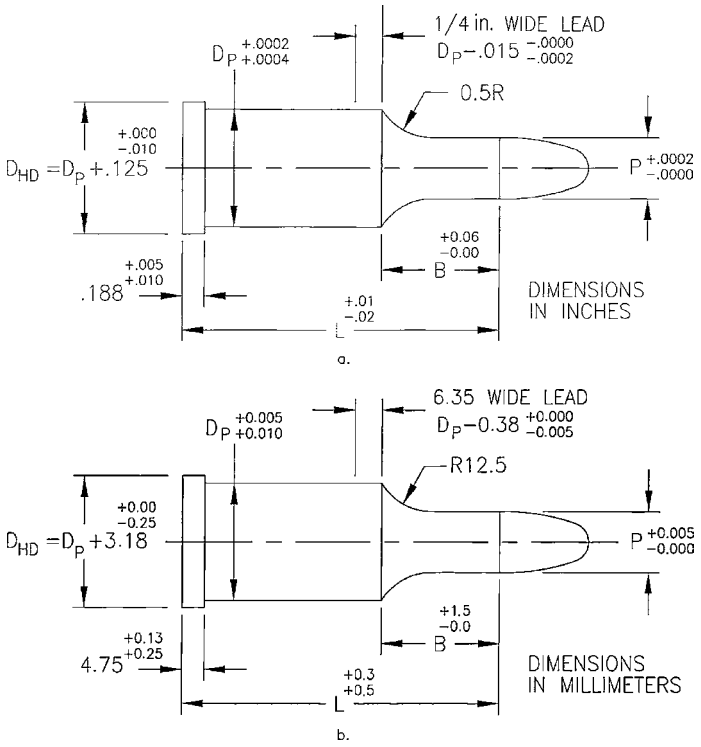

FIGURE 4-22 Detail of a pilot.

4-2-5 Guide Bushings

Guide bushings (Fig. 4-25) are inserts in the stripper, guiding and supporting the punches and protecting the stripper plate from wear caused by the die operation. These bushings are hardened inserts, headed or headless, press-fitted into the plate, with slip-fit openings to contain the punches. Their countersink-shaped inner openings aid in the centering of the punch during the die operation.

The tolerance range of the guide bushing's inner openings is not as precise as that of cutting areas. The opening itself is usually made +0.001 in. (0.03 mm) greater than the size of the punch, with tolerance of +0.001/–0.000 (+0.03/–0.00 mm).

Mounting of guide bushings in the stripper plate is the same as mounting of any other die member (Fig. 4-26). The head is always loose, sometimes even left outside the stripper's thickness (Fig. 4-26*b*). Bushings' heads are oriented around the stripper's upper surface for a majority of punching work. Only where greater stripping forces are expected, the head may be turned upside down, toward the stripper block's bottom surface (Fig. 4-26*d*).

An alternative mounting method of punches, dies, and guide bushings (Fig. 4-27) uses only standard-size drills and reamers for this procedure. Where previously the same amount was added to the punch-body diameter for its head size (+0.125 in. or 3.18 mm), here the amount to be added corresponds with the availability of tooling, so that the counterbore will

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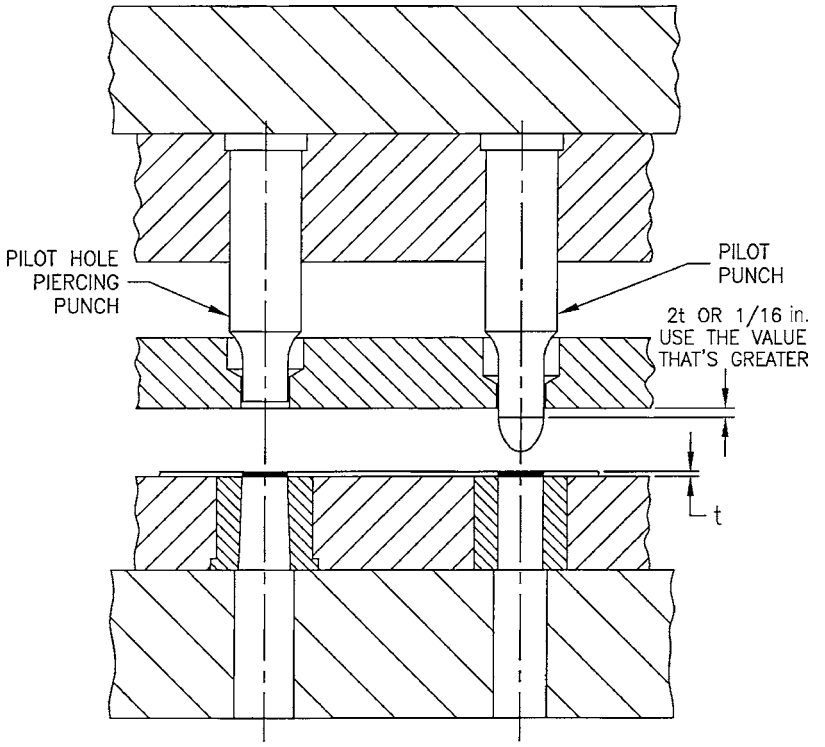

FIGURE 4-23 Function of a pilot punch.

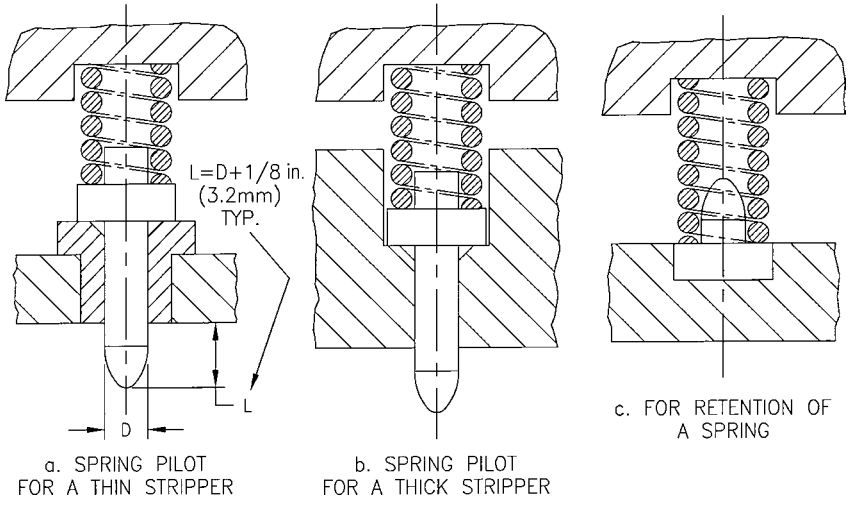

FIGURE 4-24 Spring pilots and their use.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

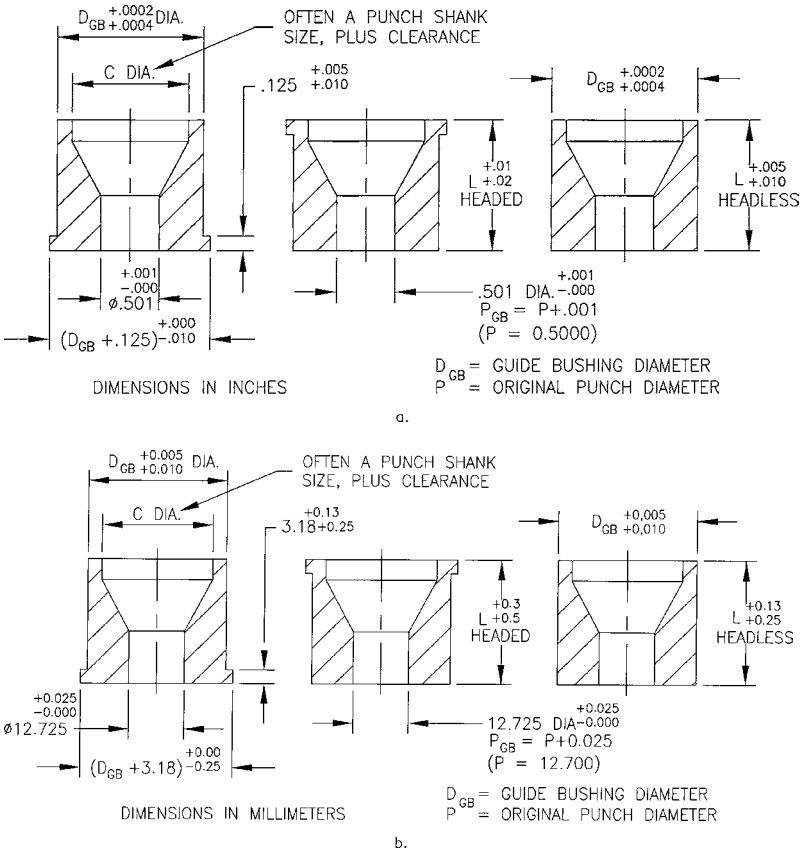

FIGURE 4-25 Guide bushings.

not be special in size. Such a counterbored pocket may be adapted to quite a narrow line of tooling, provided all punches and bushings are similarly altered to fit.

Here, the designer should be aware of the material cost and labor restrictions. If the step between the shank and head is too great, the blank size for the particular punch will also be greater, with subsequent increase in cost. The time needed for removal of a larger than usual chunk of metal will increase as well.

4-2-6 Knockouts, or Knockout Pins

In some instances, with oil present on the face of the sheet metal material as well as all over the surface of a die, the punchings, piercings, or formings, can remain attached to the face of the punch or die. Especially where the oil film allows for development of a vacuum, the parts stick to the tooling as if glued.

To remove these off the tool faces, knockout pins, sometimes called *kicker pins*, are used. They push the part away, activated either by the knockout bar of the press, or by springs. A press knockout mechanism is preferred to springs, since the spring action begins immediately on retrieval of the upper half of the die. This way the spring force keeps the

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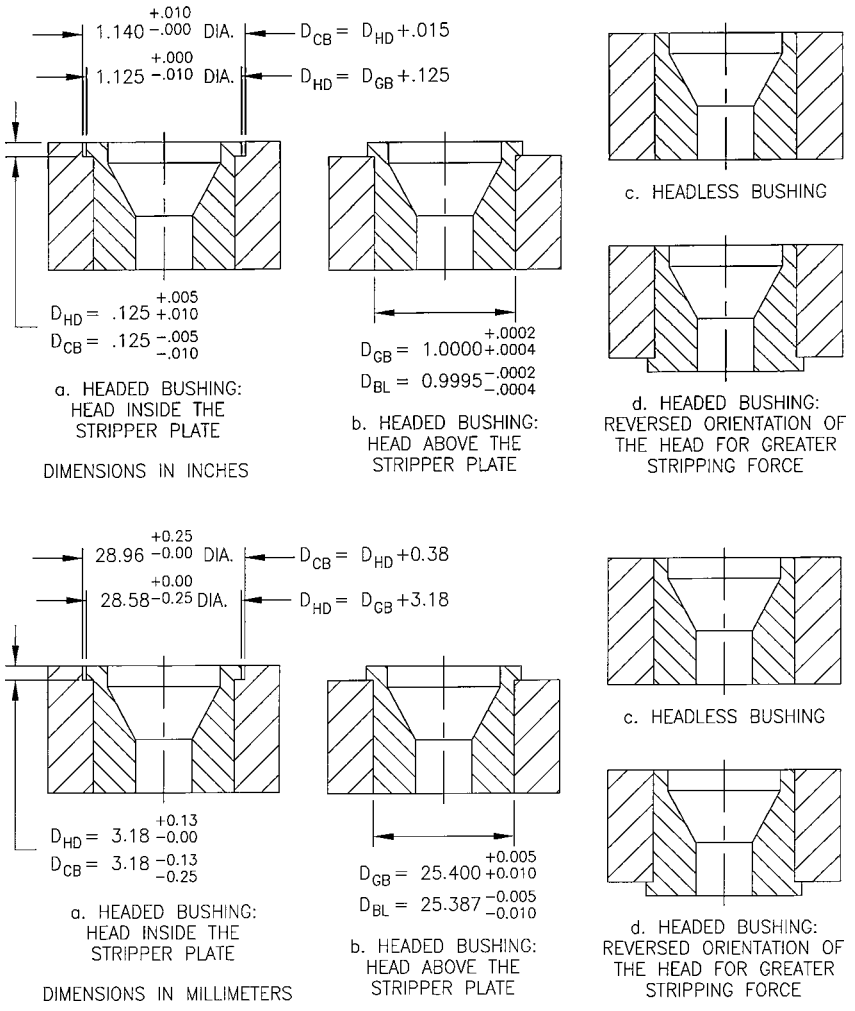
1.140 +.010 −.000 DIA.
1.125 +.000 −.010 DIA.
$D_{CB} = D_{HD} + .015$
$D_{HD} = D_{GB} + .125$
$D_{HD} = .125^{+.005}_{+.010}$
$D_{CB} = .125^{-.005}_{-.010}$
a. HEADED BUSHING: HEAD INSIDE THE STRIPPER PLATE
DIMENSIONS IN INCHES
$D_{GB} = 1.0000^{+.0002}_{+.0004}$
$D_{BL} = 0.9995^{-.0002}_{-.0004}$
b. HEADED BUSHING: HEAD ABOVE THE STRIPPER PLATE
c. HEADLESS BUSHING
d. HEADED BUSHING: REVERSED ORIENTATION OF THE HEAD FOR GREATER STRIPPING FORCE
28.96 +0.25 −0.00 DIA.
28.58 +0.00 −0.25 DIA.
$D_{CB} = D_{HD} + 0.38$
$D_{HD} = D_{GB} + 3.18$
$D_{HD} = 3.18^{+0.13}_{-0.00}$
$D_{CB} = 3.18^{-0.13}_{-0.25}$
a. HEADED BUSHING: HEAD INSIDE THE STRIPPER PLATE
DIMENSIONS IN MILLIMETERS
$D_{GB} = 25.400^{+0.005}_{+0.010}$
$D_{BL} = 25.387^{-0.005}_{-0.010}$
b. HEADED BUSHING: HEAD ABOVE THE STRIPPER PLATE
c. HEADLESS BUSHING
d. HEADED BUSHING: REVERSED ORIENTATION OF THE HEAD FOR GREATER STRIPPING FORCE

FIGURE 4-26 Mounting of guide bushings.

shedder down, on the face of the die, along with the part. The thin oil film between the part and the die may retain the part to such a degree that the shedder returns upward with no part to shed off, while the die ends up with a part attached to its surface.

The press knockout mechanism functions differently. Here the part may remain attached to the shedder while the ram, along with the upper half of the die, ascends. Only later, toward the end of the ram's movement, when the knockout mechanism is activated, it effectively strips the part off the upper half of the tooling. This is the reason, such knockout action is called positive.

Knockout pins, knockout pads, or similar arrangements, can be used to remove the sheet metal parts off the face of the die, to remove the parts trapped inside their tooling, or to lift up the sheet while it is being forwarded through the die.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

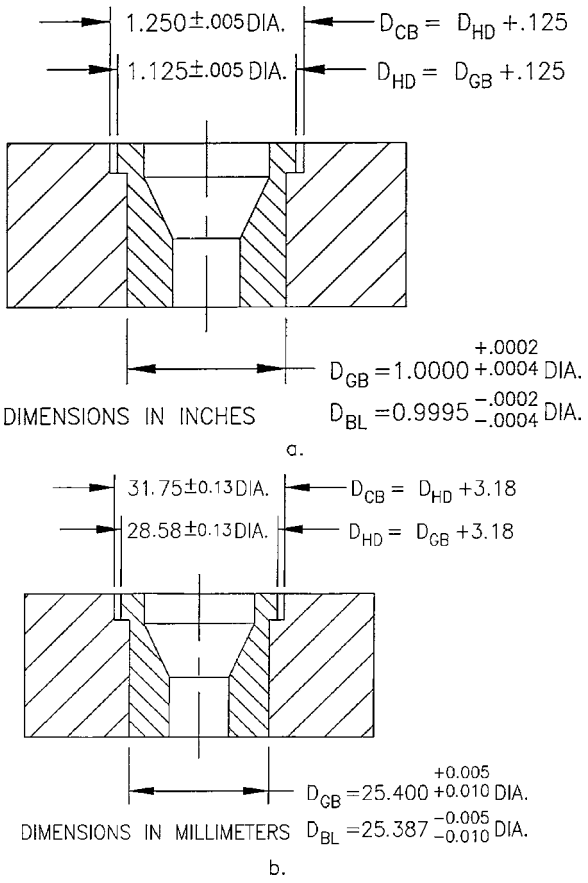

FIGURE 4-27 Alternative method of mounting of bushings, punches, and dies.

Knockout pins are rather small in diameter, and are usually placed in the close proximity to the cutting surface of the punch, as shown in Fig. 4-28. There are several variations of these arrangements, with dependence on the application they are intended for. Where stripping the sheet-metal strip, the knockouts are most often placed next to the punch; where stripping the part itself, the pins are used to push a shedder, surrounding the punch's body. Sometimes, a single knockout pin is placed coaxially with the punch.

The lifting type of knockout prevents the cut or formed part from falling below the upper surface of the die. This type of part ejection is sometimes necessary where return blanking, flange forming, drawing, and similar operations are performed.

During the cup-forming operation, depicted in Fig. 4-29, the upper half of the die slides down, cutting the blank out of the sheet with the outer edge of its forming punch. The lifting pad moves along, attached to the punch plate with lifting rods. The whole array bottoms on the retaining ring, which secures the forming die in its location. Lifting rods' heads fit into the clearance openings of the retaining ring.

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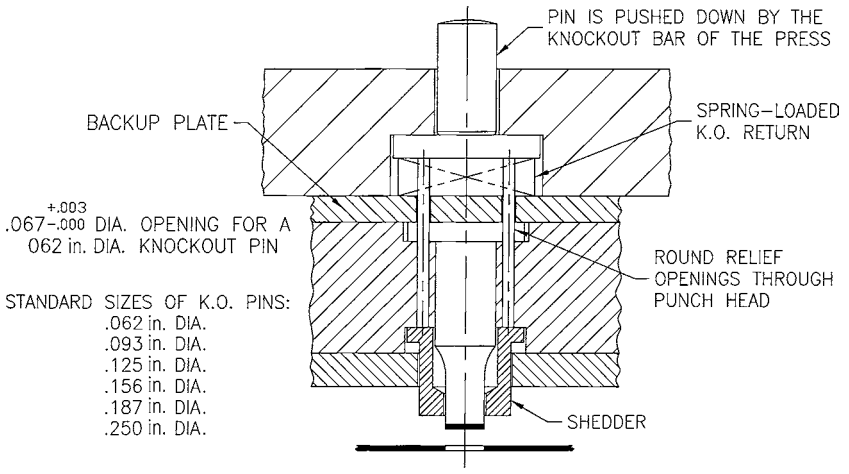
PIN IS PUSHED DOWN BY THE KNOCKOUT BAR OF THE PRESS
BACKUP PLATE
SPRING–LOADED K.O. RETURN
+.003
.067–.000 DIA. OPENING FOR A 062 in. DIA. KNOCKOUT PIN
ROUND RELIEF OPENINGS THROUGH PUNCH HEAD
STANDARD SIZES OF K.O. PINS:
.062 in. DIA.
.093 in. DIA.
.125 in. DIA.
.156 in. DIA.
.187 in. DIA.
.250 in. DIA.
SHEDDER

FIGURE 4-28 Positive knockout system (three K.O. pins per assembly).

At the end of the forming sequence, when the upper half of the die moves up, the centrally located knockout pad forces the part out of the forming punch area. Lifting rods move along, pulling the lifting pad behind. When the lifting pad comes up flush with the die block, it provides a support to the formed cup before it gets removed from the die-working area. Naturally, the part has to be blown off the face of the die with air, or be manually removed with tongs.

4-2-7 Strippers

Stripping of parts off the face of the tooling is a complex problem, influenced by the thickness of material and its type, by the surface finish of the strip, and by the surface condition of the tooling as well.

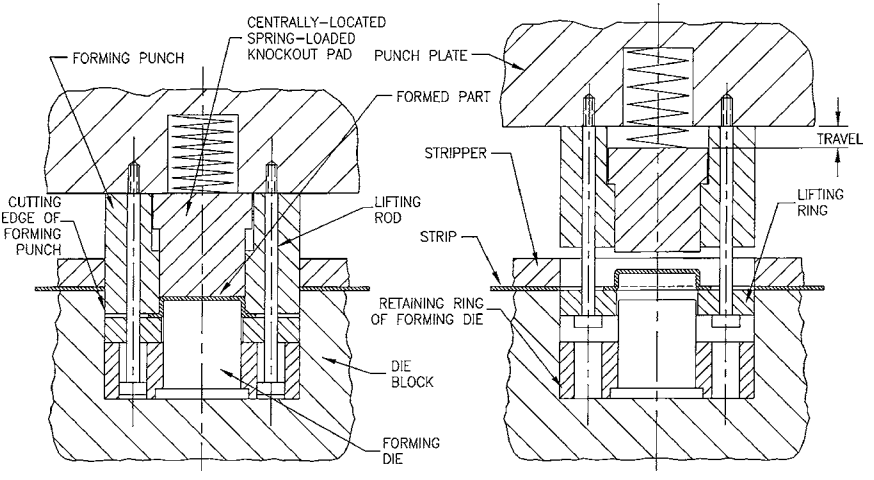

FIGURE 4-29 Lifting-type of knockouts.

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The stripping of parts is further complicated by the prevailing manufacturing procedures, since all conventional metalworking machinery leaves circumferential grooves in the surface of a machined part. The sheet-metal material, forced by the pressure of tooling, may sometimes be coerced into fitting within these grooves in some sensitive sections and thus may generate a serious stripping problem.

For this reason, all problem-prone surfaces should obtain their final finish by some longitudinal grinding or polishing process, which may level these circumferential grooves and perhaps even replace them with slight lengthwise arrangements.

Another influence detrimental to parts' stripping is the emergence of vacuum between the cut metal and its tooling. This problem is discussed later in this chapter, with some possible remedial tooling alterations shown later in Fig. 4-53.

4-2-7-1 Stationary and Spring Strippers. Strippers, as used in the die work, are either stationary (nonmoving) or spring-loaded (moving). Stationary strippers are low in cost when compared to spring strippers. Therefore, spring-backed stripping arrangements should be used with thin, fragile punches, where the immediate stripping action may prevent their breakage.

Spring strippers are of advantage also where additional flattening or material-retaining function is needed or considered beneficial. Such retaining action is usually utilized in drawing, flanging, or other forming operations.

Stationary strippers are provided with a milled channel made to accommodate the strip material. It retains the strip in a fixed location, preventing it from moving anywhere, up, down, or sideways. Naturally, this type of stripper is not adequate where the height of a part is increased during the die operation, such as the height of drawn, formed, embossed, or flanged parts.

The stationary stripper (Fig. 4-30) is attached to the die block and it can be using the same screws and dowel pins necessary for attaching the die block to the die shoe. This way, a single set of dowel pins provides for the alignment between all plates, and a single set of screws is used for their attachment.

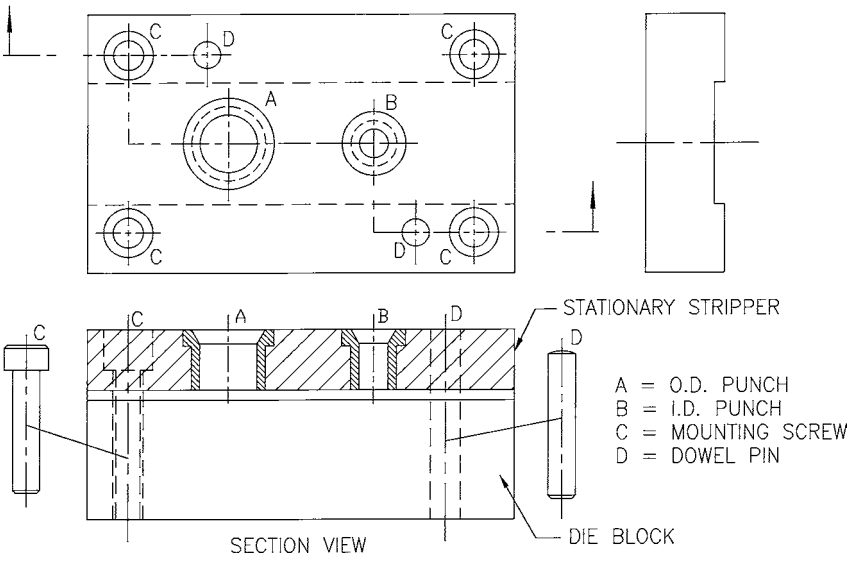

FIGURE 4-30 Stationary stripper.

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The holes containing dowel pins must be precision-reamed throughout all plates (shown later in Fig. 4-62). But the holes for screws cannot be tapped all the way through, as a misalignment, binding, and a host of other difficulties will be encountered during assembly. Openings for screws must be relief openings all the way through the blocks, no matter what their number or height should be, with only the final block being tapped, as shown later in Fig. 4-61.

Spring strippers (Fig. 4-31) are utilized where an increase in the height of a part is encountered. They also provide for much firmer stripping action, while acting partially as spring pads during the cutting, forming, or drawing activity of the die.

Spring strippers are attached to the punch plate, which makes them slide along with the movements of the ram.

Even with all the precision work and tight tolerances, a stripper plate can sometimes be observed as "floating," especially where retained by stripper bolts only. In such instances, a guided stripper is recommended, particularly where some fine punches are being used in the die assembly (see Fig. 4-32). Guided-stripper plate should also be utilized with higher press speeds, so that possible movements of the stripper plate will not endanger the rest of the tooling.

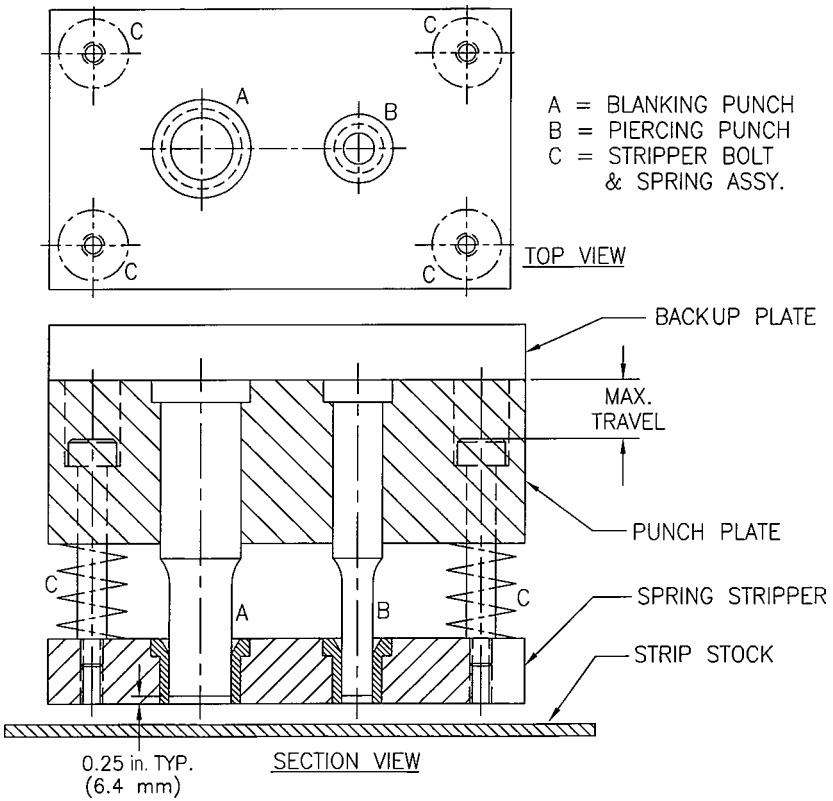

FIGURE 4-31 Spring stripper.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

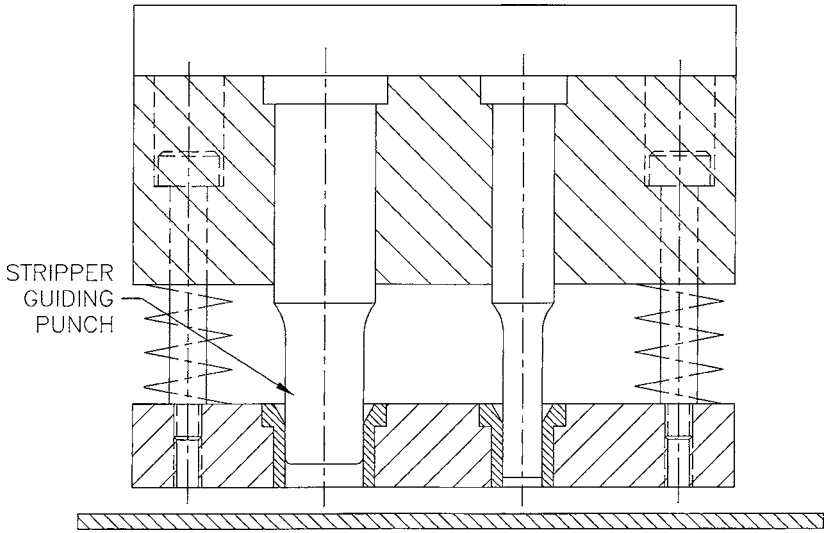

FIGURE 4-32 Guided spring stripper.

Material of the stripper plate must be ground on both sides and perfectly square. Where serving as a pressure pad, or where some wipe forming is involved, roughening of that surface may be needed, with dependence on testing for that particular operation and for that particular sheet-metal material. For the purpose of testing and adjustment, prehardened hot-rolled steel, HRc 35-38 is often recommended.

A minimum stripper-punch clearance per side should be anywhere from 0.001 in. (0.025 mm) up to a maximum of two-thirds of the material thickness. Again, testing and prevailing manufacturing practice should guide our choices.

4-2-7-2 Strippers for Drawn Parts. A stripper for thin-walled drawn parts is shown in Fig. 4-33*a*. This stripper is made of four circular segments, held together with a wire ring placed along their circumference.

The part, when forced by the action of a punch through such a stripping arrangement, coerces the segments to yield to its mass. This is accomplished with the assistance of the segments' central countersunk shape, shown in an enlarged detail. A minute movement of the whole assembly away from the center and against the holding force of the wire may be expected as well.

As the drawn shell passes through, its way back is blocked by the sharp edges of the opening in the segment ring.

The stripper in Fig. 4-33*b* is somewhat more positive in its action. Here the ring is replaced by two separate segments (shown in detail below the illustration), sliding toward the central punch under the force of springs. The material is pushed through, aided in its entry by the slant in the segments' surface. They immediately snap back, toward the body of the punch, allowing for no return of the shell.

This arrangement is found quite useful with thick-walled parts; thin shells may become torn by the stripping action applied to such a small area of their circumference. For thin-walled parts, a full ring of segments would be more appropriate, provided their construction allowed for a more controlled sliding-away and coming-back action.

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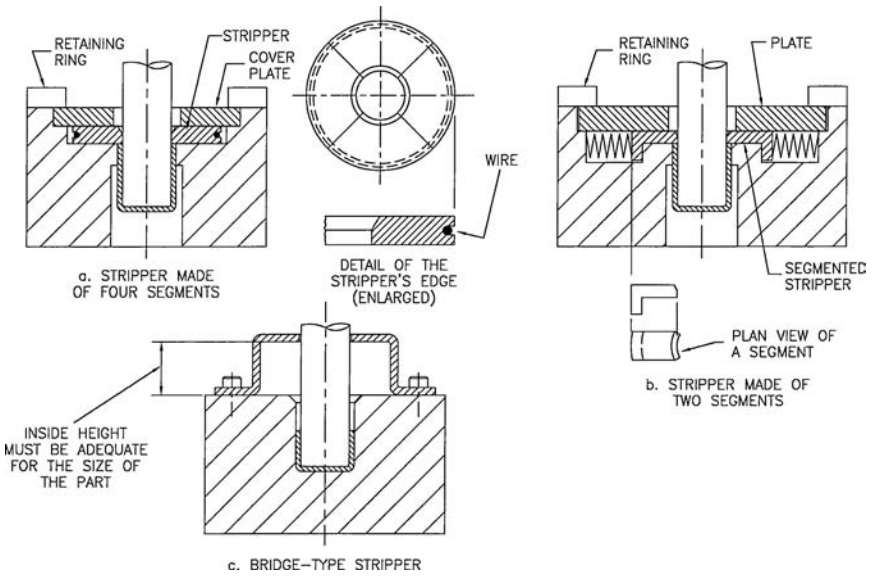
RETAINING RING
STRIPPER COVER PLATE
a. STRIPPER MADE OF FOUR SEGMENTS
WIRE
DETAIL OF THE STRIPPER'S EDGE (ENLARGED)
RETAINING RING
PLATE
SEGMENTED STRIPPER
PLAN VIEW OF A SEGMENT
b. STRIPPER MADE OF TWO SEGMENTS
INSIDE HEIGHT MUST BE ADEQUATE FOR THE SIZE OF THE PART
c. BRIDGE–TYPE STRIPPER

FIGURE 4-33 Miscellaneous stripping arrangements.

Bridge-type stripper often called a "sky hook," (Fig. 4-33*c*) strips securely and inexpensively all kinds of shells, regardless of their stock thickness or type of material.

4-2-7-3 Minimal Thickness of Stripper Plates. The thickness of a stripper plate can be calculated by using the formula

$$h = \frac{1}{3}W + 2t \tag{4-3}$$

where h = minimum stripper plate thickness
W = stock width
t = stripped material thickness

The result should be rounded up to the nearest fractional dimension in the eighths range, such as 0.375 in., 0.50 in., 0.625 in., 0.750 in., and so on.

4-2-8 Stock Guides

The width of coiled material comes within a certain tolerance range. As can be expected, the tighter this range is, the higher the cost of that coil. Additionally, quite often the material's edges can be somewhat wavy and uneven. Bowing of the coil can be present as well, along with other imperfections. These factors have to be borne in mind when designing and making the stock guides for a progressive die.

Where heavy piloting is being utilized, the condition of the edges could be sometimes ignored and the edges may remain unguided until the end, when sheared off. There may be other cases, where the condition of strip's edges does not matter and the whole strip is

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utilized, as is. But where the overall width is of importance and where some accurate work has to be performed, a correct guidance of the strip is important.

To guide a strip across the face of a die, stock guides are utilized. These devices can be of various forms and shapes.

A set of pins, a set of blocks positioned alongside a strip, can be considered stock guides. Often, continuous, channel-type guides (shown in Fig. 4-34*a*) are used in the progressive die work. These are constructed so as to prevent the strip not only from moving aside but from following the upper die member in its movement during the die operation. This type of guiding arrangement, however, does not protect the sheet from bulging up when being pulled on by any of the punches. Such protection can be provided by substituting the side rails with a stationary stripper (Fig. 4-34*b*).

The width of stock-guiding channels, W_{total} should be equal to

$$W_{\text{total}} = W_s + W_{\text{st}} + W_b + W_{\text{ba}} + W_c \tag{4-4}$$

where W_s = width of the strip material
W_{st} = strip tolerance
W_b = guide block's tolerance range
W_{ba} = guide block's assembly tolerance range
W_c = clearance between the strip and its guides

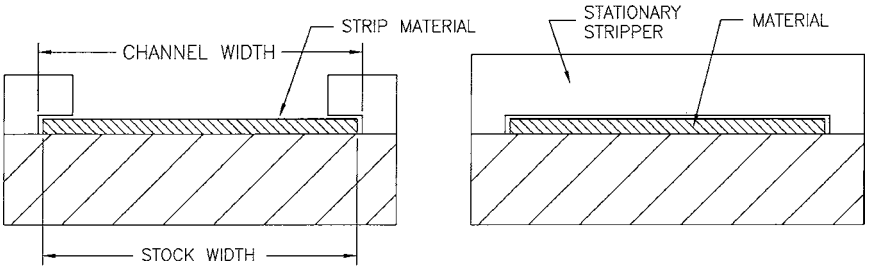
Where such increase in the guiding channel width would be detrimental to the produced parts, a tolerance-tightening use of pilots can be utilized.

The most popular approach to the strip guiding is a so-called "French stop" (shown in Fig. 4-35). This type of stop not only prevents the material from advancing beyond the planned distance; it also guides it along the way. It negates all the problems related to the strip tolerance ranges and edge waviness, while ensuring the proper feeding of the material.

The punch, which is used to produce the notch, is usually rectangular in shape, with the longer side equal to the progression of the strip. It cuts with two of its sides only; that along the strip length and the end of the notch. The notch is pierced in one operation and used for banking against a fixed block in the next.

In some situation, where the strip width is under 6 in. (150 mm), only one of its sides could be notched; strips over 6 in. wide should be notched on both edges. The width of the notched area is usually recommended at 1.5*t*.

A similar alternative, shown in section "A-A" of the same illustration, uses a side bend to stop the advancing strip. In this case, not only the bend provides for the control of strip's progression; it further stiffens its width, removing some of the bow. Naturally, the stop on which the bend is to bank has to be spring-loaded.



a. MATERIAL–RETAINING GUIDES
WIDTH = $W_S + W_{ST} + W_B + W_{BA} + W_C$

b. ENCLOSED STATIONARY STOCK GUIDE FUNCTIONING ALSO AS A STRIPPER

FIGURE 4-34 Stationary stock guides.

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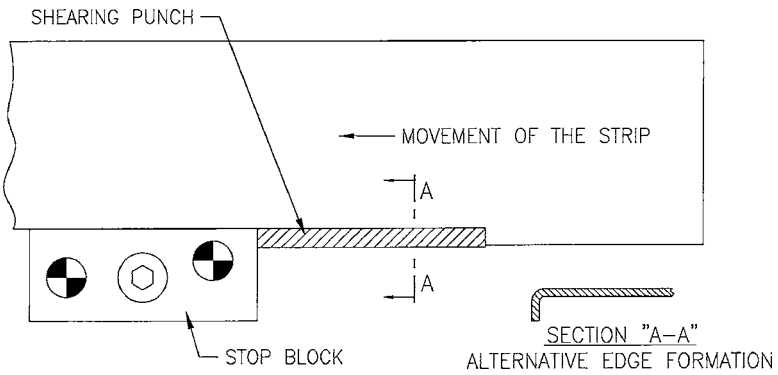

FIGURE 4-35 Lancing of the strip side. (i.e., *French stop.*)

Another variation of this approach is a downward lance, shown in Fig. 4-36. Here the progression is controlled when the lanced tab comes into contact with a spring-loaded stop. In the next station, the lance is flattened and pushed back into the strip, so that not to obstruct further progression.

The roller stock pusher (Fig. 4-37) enhances its stock-guiding capacity by combining it with greater accuracy. The hardened roller, contained at the tip of the unit, contacts the edge of a material and allows it to slide past by rotating along with its movement. The roller is held against the material's edge by the force of a spring, which allows for a width variation of the strip, rendering any additional adjustment needless.

The material-positioning device (Fig. 4-38) is mounted on the upper half of the die, and it moves up and down with the movement of the ram. During the downstroke, the long arm trips over the edge of a sliding block and pushes it toward the edge of the material. The sliding block, restricted in its movement by a pin, is sandwiched between the die block and the stripper. The tension adjustment of the slide-pushing arm's pressure is in the range of 2 to 20 lb (1–10 kg).

4-2-9 Stock Supports, Stock Lifters

Stock-supporting rails, as used in Fig. 4-39*a*, allow for the strip's travel above the die surface. This may be found quite helpful where the height of the strip increases because of drawing, forming, or other height-altering process.

Stock lifters (Fig. 4-39*b*) are utilized where the strip is forced down during the die operation and where its return to the original height is desired. Such need arises with many parts,

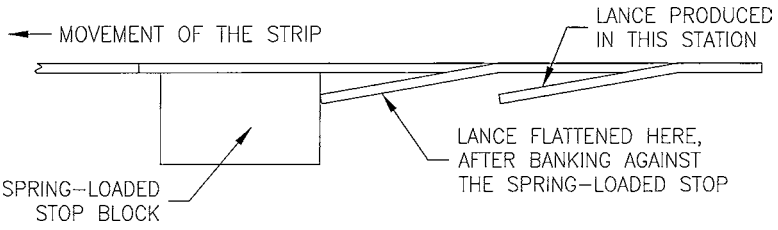
MOVEMENT OF THE STRIP
LANCE PRODUCED IN THIS STATION
LANCE FLATTENED HERE, AFTER BANKING AGAINST THE SPRING–LOADED STOP
SPRING–LOADED STOP BLOCK

FIGURE 4-36 Lanced tab as a stop.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

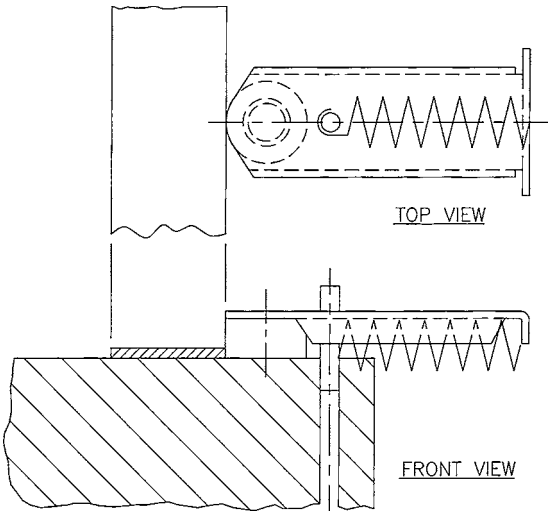

FIGURE 4-37 Roller stock pusher. (*Printed with permission from: Applied Mechanics Corp., Grand Rapids, MI.*)

altered in height, which travel from station to station, falling into relief recesses during the operational cycle of the die, from where they are to be pulled up again.

Where the height of a part is not being grossly altered, a lifter-retainer combination, such as the one shown in Fig. 4-39*c*, may be used. With the upper half of the die already up, the lifter is restricted from following along by its travel-limiting flange. When the die slides down, it exerts a pressure on the lifter as well, forcing it down, along with the strip it retains.

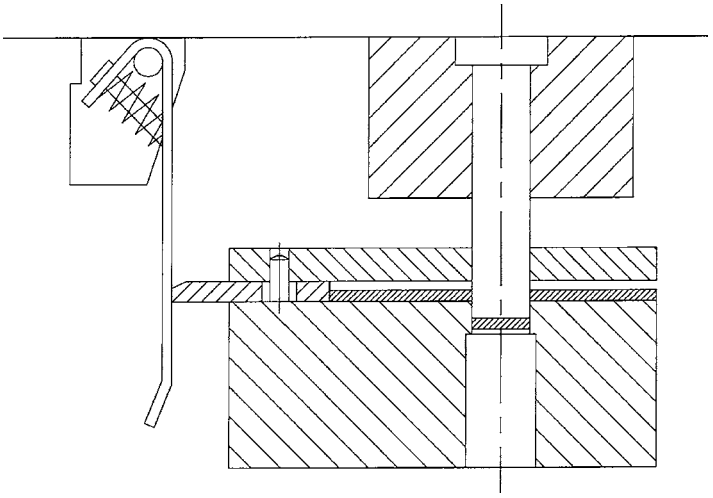

FIGURE 4-38 Material positioner. (*Printed with permission from: Applied Mechanics Corp., Grand Rapids, MI.*)

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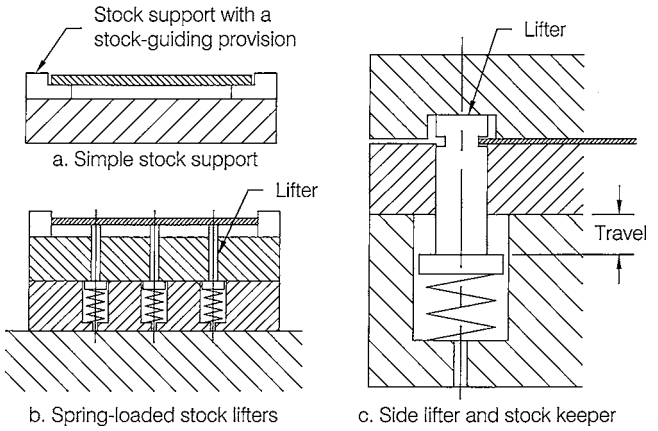

FIGURE 4-39 Stock support, stock lifters.

An adjustable version of this type of lifting device is shown in Fig. 4-40. By turning the slotted head of the unit, its position with regard to the sheet-metal strip as well as its height can be adjusted. This type of device also takes various sizes of heads, which makes its adjustability still more versatile.

4-2-10 Stops

Strip material, when first being guided into the die, must stop somewhere for the sequence of die operations to begin successfully. It is obvious that the strip should not go as far as the forming tool, which may need some preblanking work performed at the beginning. Advancing the strip too far may lead to greater than usual wear and tear of the tooling and its subsequent misalignment and breakage.

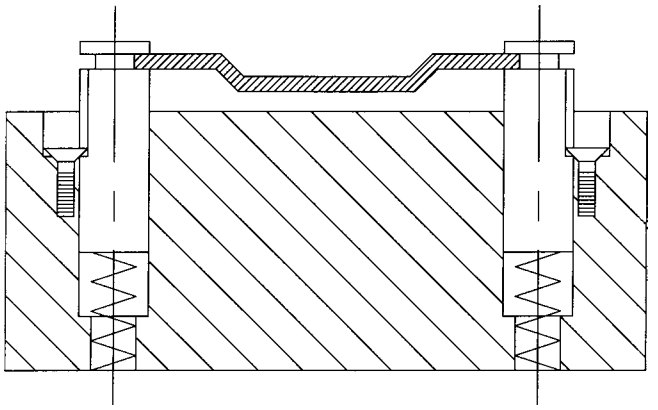

FIGURE 4-40 Adjustable stock lifters. (*Printed with permission from: Applied Mechanics Corp., Grand Rapids, MI.*)

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For that purpose, stops are introduced in the die work. The first stop, which the strip meets on its way, is usually the first pierce and blank locator, which navigates the strip in such a way that all cutting is included prior to its arrival at forming and other stations.

The arrangement shown in Fig. 4-41*a* has a stop arm placed in the path of an advancing strip. On reaching the edge of the stop plate, the strip is automatically positioned under the vital punches, and the whole stop assembly may be pulled out of its way. This little device, when spring-loaded, snaps forward as the end of the strip leaves the die and is there ready to stop the next strip to be inserted.

A fixed stop is shown in Fig. 4-41*b*, where the material can bypass the stop pin's registration surface only by being lifted up above its level.

The automatic stop in Fig. 4-41*c* is a device which slides up and down along with the movement of the ram and either

- forces the nose of the stop lever up, to release its engagement of the strip for the latter's progression (during the downward movement of the ram); or,
- releases its pressure on the lever, thus allowing its nose to come down, pushed by a force of a spring. In such a position, the lever is ready for registration and retainment of the advancing strip (during the upward movement of the ram).

A similar device attacheable to the surface of the die block is shown in Fig. 4-42. It is activated by a spring, which forces the gauge's nose toward the surface of the die block, holding it down to register the advancing strip.

A V-notch stop (Fig. 4-43) engages a V-notch cut in the side of the advancing material.

The nose of this device rides on the edge of the strip, snapping forward whenever a notch is encountered. When filling the notch, the spring force behind the latch pushes the whole strip material toward the opposite side of the channel, thus locating it under a punch.

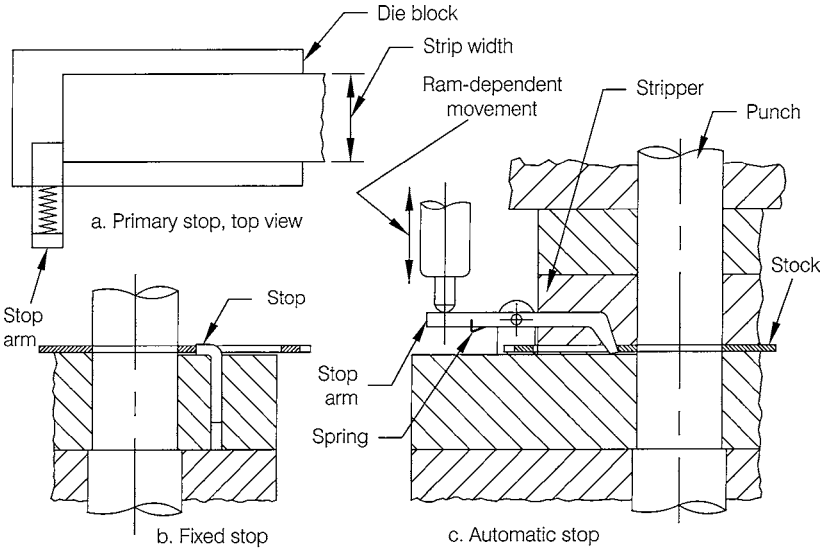

FIGURE 4-41 Stop arrangements.

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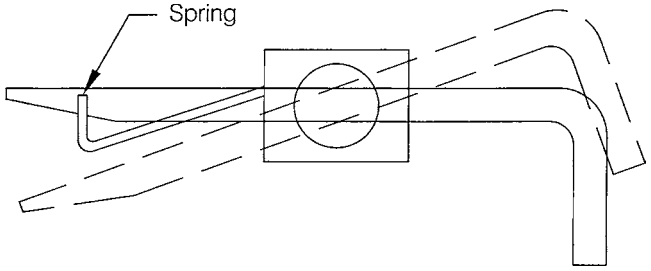

FIGURE 4-42 Automatic stop and latch. (*Printed with permission from: Applied Mechanics Corp., Grand Rapids, MI.*)

This type of stop is in its origin a finger stop, shown in Fig. 4-44, which is similarly positioned against the strip's edge, where it provides the force needed to push the material against the opposite side. The movement of the finger stop is controlled by a travel-limiting block or pin, positioned to fit within the relief slot in the stop body itself.

Various alterations of the travel-limiting slot location provide for a wide variety of applications. The side-located slot may be used with the travel-limiting function of a side block. The block with a pocket utilizes a pin to control the amount of its movement.

Some miscellaneous stopping ideas are demonstrated in Fig. 4-45. The material-deflecting pin in Fig. 4-45*b* makes the material slip over its rounded head, deflecting it down, where it leaves the die under an angle. The strip, already perforated, it easily averted from its straight path.

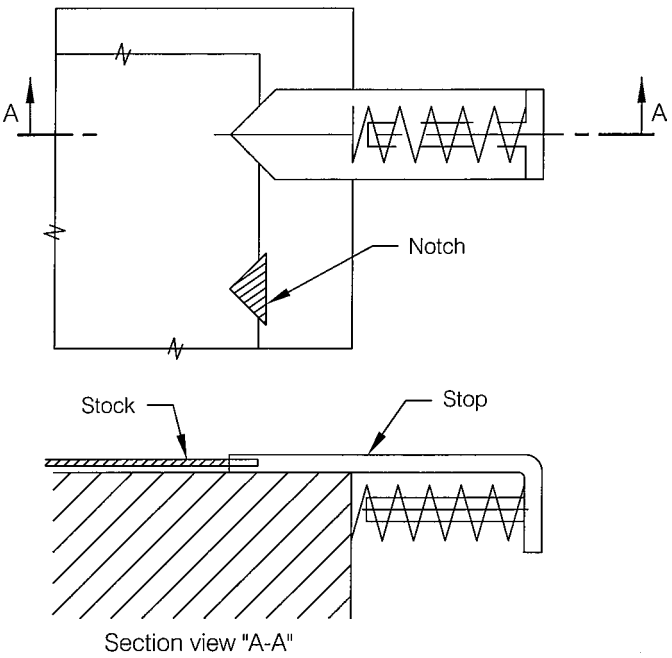

FIGURE 4-43 V-notch stop.

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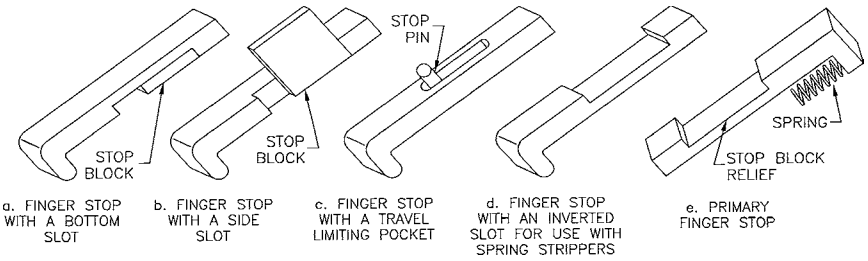
STOP PIN
STOP BLOCK
STOP BLOCK
SPRING
STOP BLOCK RELIEF
a. FINGER STOP WITH A BOTTOM SLOT
b. FINGER STOP WITH A SIDE SLOT
c. FINGER STOP WITH A TRAVEL LIMITING POCKET
d. FINGER STOP WITH AN INVERTED SLOT FOR USE WITH SPRING STRIPPERS
e. PRIMARY FINGER STOP

FIGURE 4-44. Finger stops.

A material stop, allowing for eccentric positioning, is shown in Fig. 4-46. The whole unit can be rotated around a counterbore and secured in its final position by a steel ball emerging from its side. The steel ball is pushed out by the movement of a setscrew's cone point, which also retains it in the attained position.

The progressing strip stock is stopped in its movement on encountering the spring-loaded pin. When pushed down, the pin does not obstruct its advancement, provided there are no openings in its path.

A cam-operated slide (Fig. 4-47) delivers a fixed amount of adjustment to the sheet-metal strip. Attached to the upper half of the die, it moves down with the ram, driving the slide block toward the edge of the material (in its lowest position) and away from the strip (when moving up).

Electronically controlled material gauging units have a highly controllable area of function. Good gauging properties of this type of equipment can be made consistent in spite of variability of material thicknesses and sheet width.

4-2-11 Pressure Pads

Pressure pads are actually small localized strippers, which operate on a slightly different basis. Instead of stripping parts off the tooling, they eject the pieces by pushing them out of the tooling.

By bringing the upper part of the die down on the work, as illustrated in Fig. 4-48, the spring pad is squeezed to its utmost position, up or down, whichever is appropriate. So restrained, the pad exerts a holding force on the sheet strip, not allowing the material to move or to be pulled along by the forming or bending action.

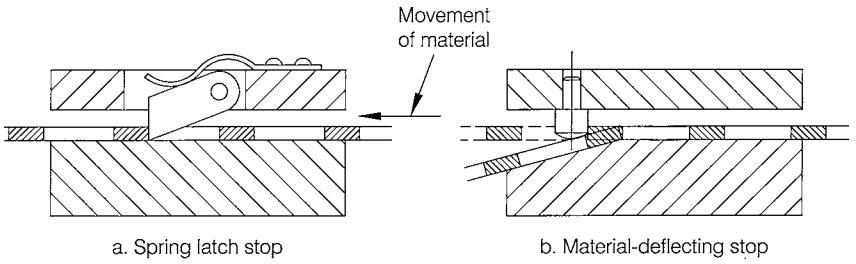

FIGURE 4-45 Miscellaneous stops.

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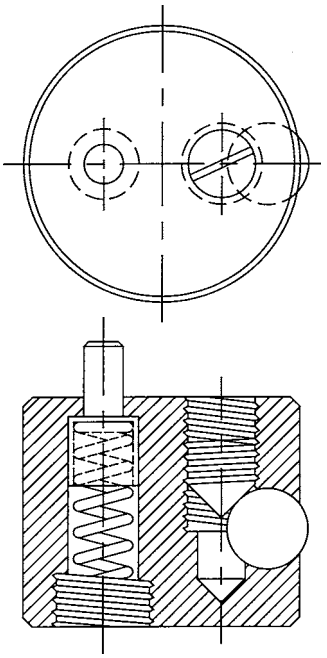

FIGURE 4-46 Eccentric gauge stop. (*Printed with permission from: Applied Mechanics Corp., Grand Rapids, MI.*)

During the upstroke of the press, the pad, forced by the action of its springs shoots forward, ousting the formed part from within the forming tool. Its opposite member, a forming block, provides the supportive action and may or may not contain some ejecting arrangement, either within its construction or beside it.

The necessity of additional spring ejecting force is determined by the shape of a part, by the depth of the formed section, material type and condition, aside from other influences.

The retention of the pad in a floating position is provided by shoulder screws. (Figure 4-49 shows pad retainers.) These not only secure the block in a relatively fixed position, they also control the length of its travel by the amount of space between the counterbore's surfaces and the bottoms of their heads. This space should be equal to the required travel distance, plus the life of the die.

If necessary, bolt heads may be shimmed for the proper distance, with some shims being removed during each sharpening.

In replacement of stripper bolts, which are used for the retention of spring-loaded blocks, pad retaining studs may be utilized. These are firmly attached to the pad by a socket head cap screw. Flat portions on their body diameter serve in assembly as an area for wrench application or as key flats protecting against rotation.

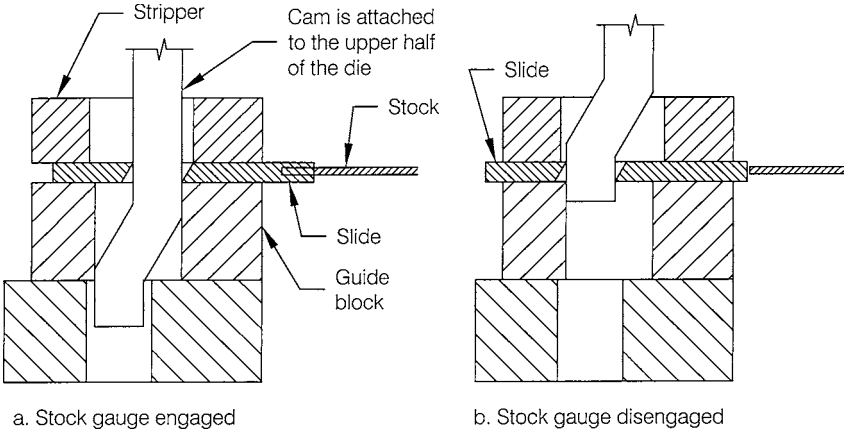

FIGURE 4-47 Cam-operated stop.

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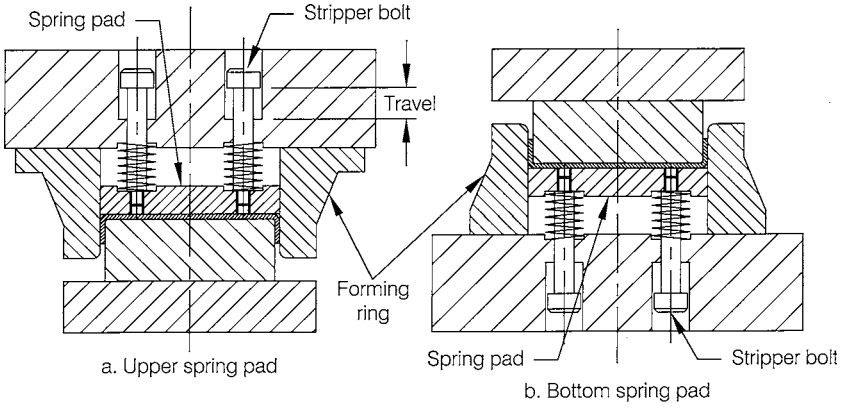

FIGURE 4-48 Pressure pads.

4-2-12 Nests

Some operations, especially shape altering or finishing operations such as shaving, restriking, precise forming, or drawing, require nests (Fig. 4-50).

Solid-block nests are utilized in empty stations of a progressive die, where they accommodate the formed part during the work cycle of a die, so that it will not be smashed and flattened by its downstroke action. The part may still be attached to the strip on its way to the final blanking station (Fig. 4-50*a*).

During the upstroke, the strip material is forced up as well by the action of stock lifters and stock feeding devices. By such movement, it pulls the nested objects along on its way through the die.

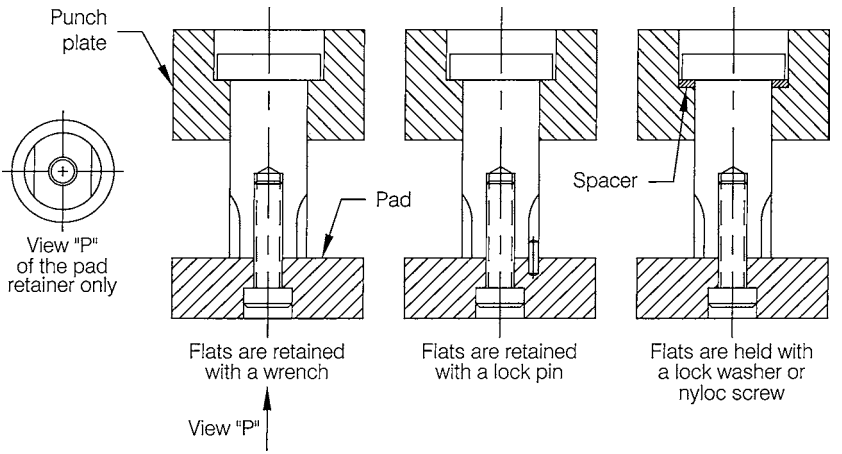
Punch plate
View "P" of the pad retainer only
Pad
Spacer
Flats are retained with a wrench
View "P"
Flats are retained with a lock pin
Flats are held with a lock washer or nyloc screw

FIGURE 4-49 Pad retainer. (*Printed with permission from: Applied Mechanics Corp., Grand Rapids, MI.*)

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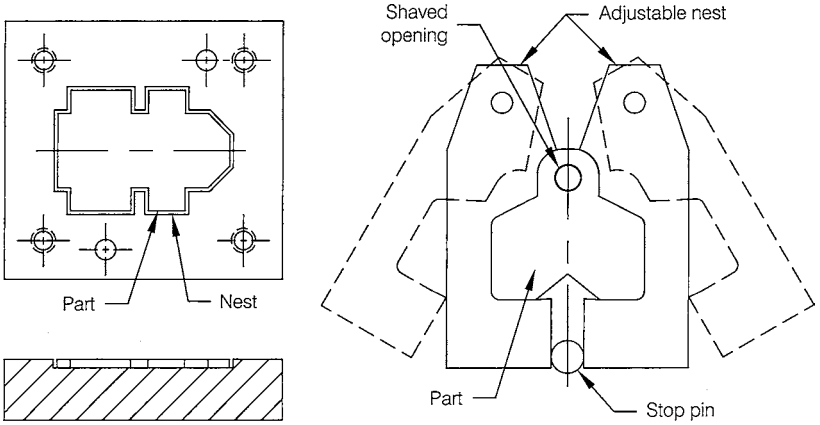

a. Solid-block nest

b. Adjustable nest

FIGURE 4-50 Nests.

Some nests, like those for shaving, can be adjustable to allow for easy removal and insertion of parts. Their moving portions should fit the outline of the part either all the way around or just in certain portions of it. This method of part locating will provide the necessary accuracy in positioning, where, for example, an opening has to be shaved and the shaving operation is to remove only a few thousandths of material per diameter.

4-2-13 Ejecting of Parts

Spring-loaded stock lifters, pressure pins, or pressure pads may all be used as ejectors of finished parts, wherever these are not cut off in the last operation. The action of ejectors may be aided by a slant in the die surface, inclination of the press bed, or the application of compressed air.

4-2-13-1 Air Ejecting. Air ejecting (Fig. 4-51) is used with formed cups and other formed shapes. It may also be used with flat washers and similar flat parts. Sometimes an inclination of the press bed is used in conjunction with an air-ejecting device to get the parts

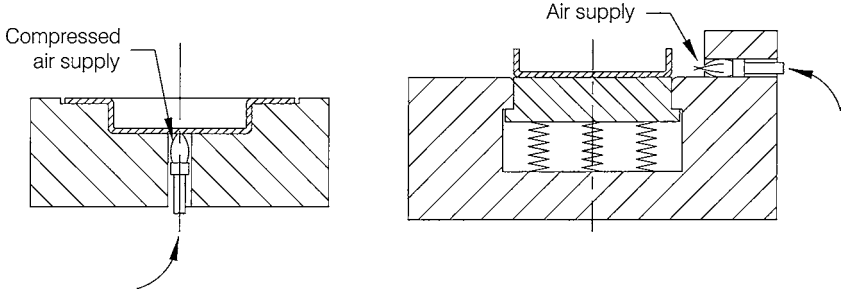

FIGURE 4-51 Air-ejecting.

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out of the working area quickly. First they are blown off the die block and, landing on the slant, are guided down into a drum, standing aside.

4-2-13-2 Other Methods of Parts Ejecting. There are several other methods of getting the finished parts out of the die. Some parts are cut off during the last operation; others are blanked and sent down through the die opening. Drawn parts are usually forced down in the last drawing station unless their flanges are to be trimmed, in which case the (last) trimming station disposes of them either through the die opening or by blowing them off the face of the die block with air.

Round blanks, such as washers or slugs, are most often disposed of by being forced down through the opening in the die bushing. For that reason, the inner diameter of the die opening increases in size, with the hole cross section tapered, usually under an angle of 1.5 to 2°, or 0.004/0.006 in. (0.10/0.15 mm) per side, up to 0.009/0.011 in. (0.20/0.30 mm) per side.

The continuation of this opening through all subsequent blocks is achieved by increasing its size $+^{1}/_{64}$ in. (0.4 mm) with every new block it encounters.

If the opening for slug removal is to be straight, its diameter should be made $^{1}/_{64}$ in. (0.4 mm) greater than the diameter of the cutting portion. A positive tolerance range in the vicinity of +0.002/–0.000 in. (+0.05/–0.00 mm) should be chosen for such a hole (see Fig. 4-52*b*).

A problem with small slugs may sometimes be encountered, as they tend to stick together and block up the passage. For that reason, slanted relief openings are placed in their path, drilled under an angle through the backup plate, as shown in Fig. 4-52*c*.

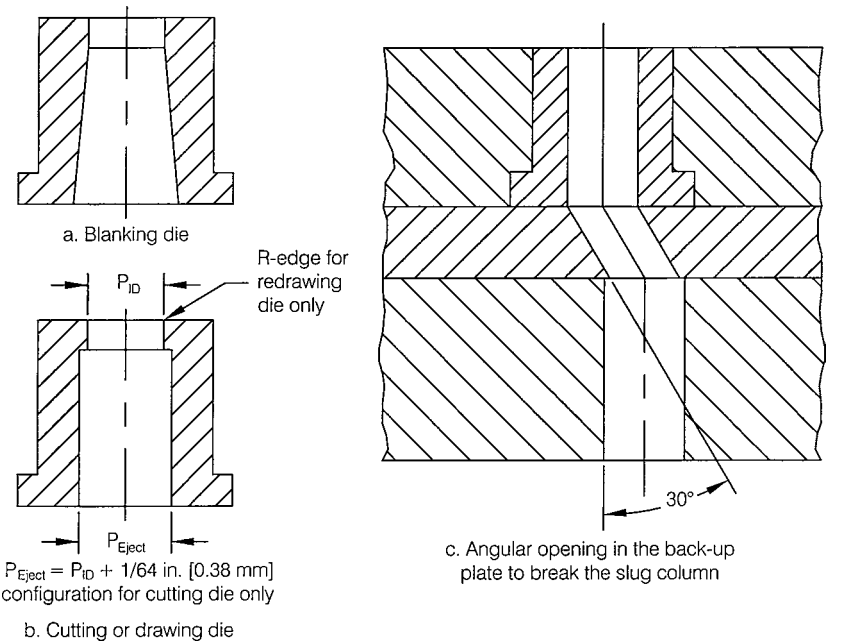
a. Blanking die
R-edge for redrawing die only
P_{ID}
P_{Eject}
$P_{Eject} = P_{ID} + 1/64$ in. [0.38 mm] configuration for cutting die only
b. Cutting or drawing die
30°
c. Angular opening in the back-up plate to break the slug column

FIGURE 4-52 Ejecting of part through the die opening.

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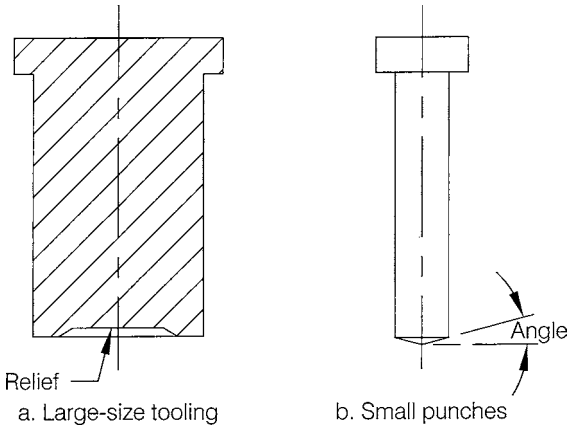

FIGURE 4-53 Punch face alterations.

Drawn parts, as already mentioned, are often sent out of the die through the opening in the drawing die itself. The fact that the drawing portion of the die bushing consists of but a short section of its total length, with an increase in diametral size afterward, only aids the ejection of parts. (See earlier Fig. 4-33 for illustration.)

However, pieces of metal stick not only to each other but to their respective tooling as well, which is often due to the emergence of vacuum between the two. The tool, being pressed hard toward the material sheet, squeezes out all the air from the place of contact, attaching the cut shape to its surface. Such parts are very difficult to strip, and sometimes only the alteration of tooling can alleviate this problem.

With large-sized punches, the inner portion of the tool may be removed, as shown in Fig. 4-53*a*. Such a recess will limit the possible entrapment of air to the area of the ring of contact, which, with the slightest bending of the cut metal, will lose its holding power altogether.

The cutting face of small punches may be shaped under an angle, as shown in Fig. 4-53*b*. Such an angle should be in a range of 1° to 2°, which should suffice to prevent vacuum-caused attachment.

However, such tools are more difficult to sharpen; because of this complication their use cannot be recommended without reservation.

4-3 MOUNTING OF BLOCKS

All the punches and dies described earlier are assembled within their respective blocks. The blocks themselves are firmly and with great precision attached to their supporting backup plates (where used) and to their die shoes. For mounting of blocks, socket head cap screws are most often utilized. The precision alignment is achieved by at least two dowel pins per block.

Usually, with smaller blocks, four screws and two dowel pins will suffice. With larger blocks, six or more screws and four dowels should be used.

4-3-1 Die Block

The die block (Fig. 4-54) is made of high-quality steel, hardened and precision ground to exact size.

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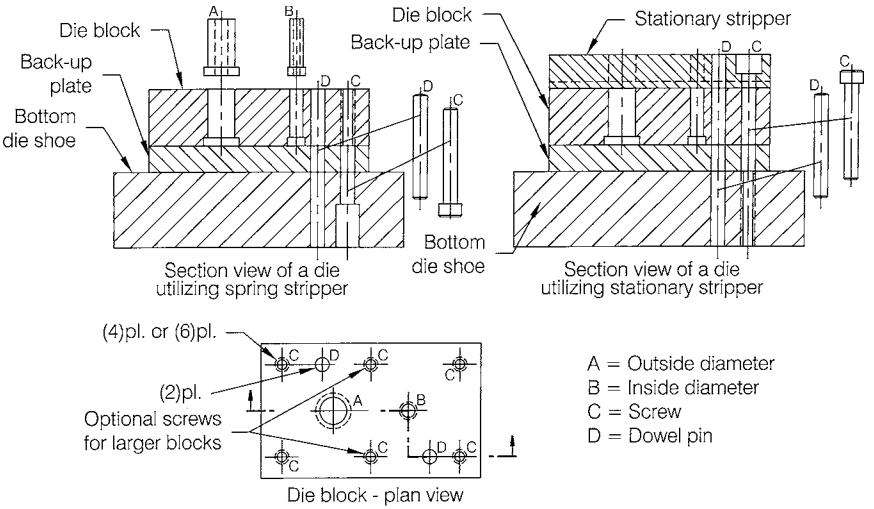

FIGURE 4-54 Die block section.

Die blocks, running in dies with a stationary stripper, would not contain tapped holes for screws; in such a situation the screws are inserted off the stripper's top surface, with counterbores in the stripper plate, relief holes through all the blocks, and a final tapped hole in the bottom die shoe.

With a spring stripper, which is not attached to the die block at all, the screws for the attachment of die block are driven in from the opposite direction, which is the bottom surface of the lower die shoe. In such a case, the die block contains tapped holes, with relief openings through all the adjoining plates and a counterbore for the screw heads in the die shoe.

When dimensioning the die block for manufacturing purposes, all the dimensions should go off one opening, which should be the only one to be dimensioned off the block's edge. Cumulative dimensioning must always be avoided, as such a method creates a cumulative tolerance buildup as well.

However, when generating a program for block-drilling NC machinery, all locations should be given off the first precision-finish hole, which is the dowel pin. The first dowel pin hole should be established as a zero location for NC equipment purposes.

A common range of general tolerances is added for illustration (see Fig. 4-55). The precision-finish openings containing die bushings and dowels, must be dimensioned as shown earlier in Figs. 4-20 or 4-27. Dowel pin mounting dimensions are given later in Fig. 4-62 and Table 4-7. Screw mounting is shown in Fig. 4-61.

The positioning of the first hole off the block's edge need not be overly precise. The surface roughness, along with the variation in straightness of the edge, may be a source of headaches for the inspection department, and yet the accuracy of this location is far from important for proper die manufacturing.

However, the distances between various openings, especially those of die (punch) and dowel pin holes, are of the utmost importance, and their precise locations cannot be overemphasized.

The height of the die block can be roughly assessed using Eqs. 3-1 and 3-2, in Chap. 3. These calculations are basically evaluating the deflection of the block; the block itself is here taken into consideration as being a simple plate.

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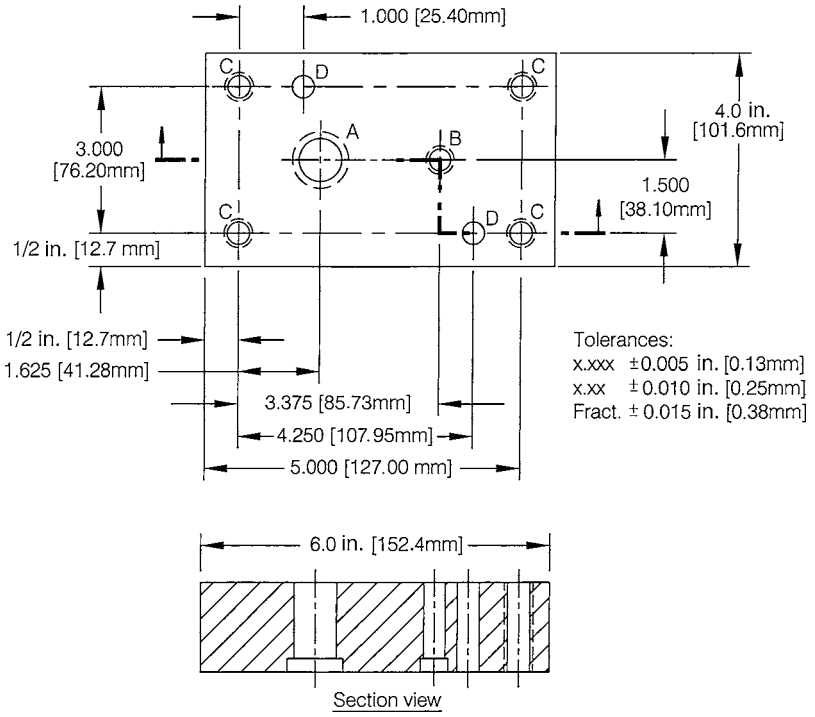

FIGURE 4-55 Die block dimensioning.

Additional evaluation of the stresses affecting the die block is based on the relationship

$$S_B \leq S_M \tag{4-5}$$

where S_B is the forming stress on the material and S_M is the allowable forming stress on the die block material.

According to Oehler's findings, the height of the block can be made equal to:

$$h \geq \sqrt[3]{P_{\max}} \tag{4-6}$$

where h is the height of the block and $P_{\max}$ is the maximum cutting, forming, or otherwise material-altering force.

We can further fine-tune our calculations with respect to the size of an opening in the die block, while taking into consideration the influence of the supporting block's shape, as shown here. We follow an assumption that the most common case is that of a round hole in a round supporting block, the following formula for the assessment of work stress, applies:

$$S_B = \frac{1.5P}{h^2}\left(1 - \frac{D}{1.5D_o}\right) \tag{4-7}$$

where S_B is the forming stress on the material and P is the cutting force. All other values are per Fig. 4-56*a*.

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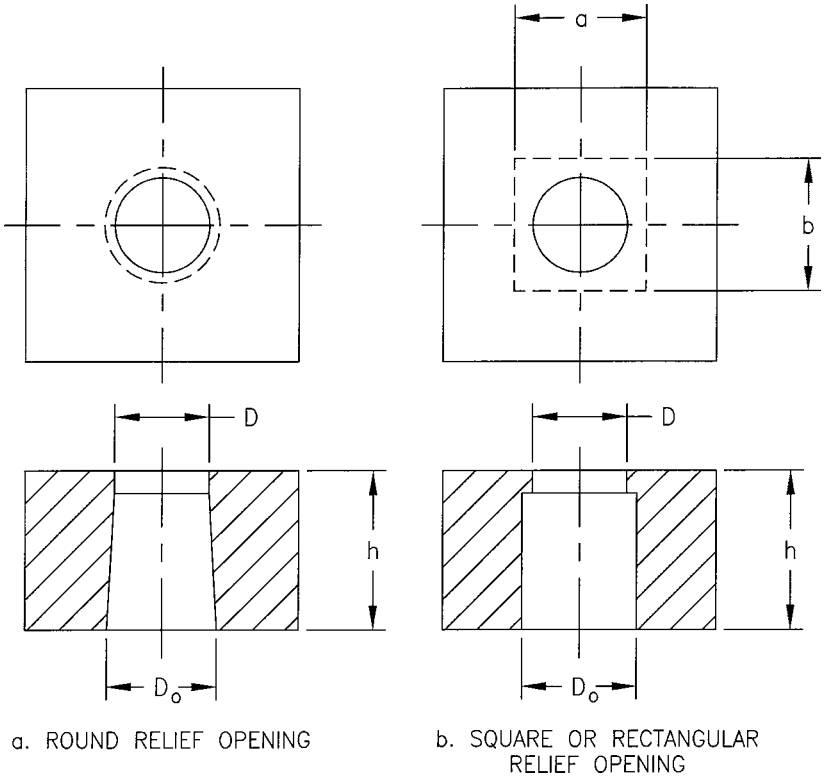

FIGURE 4-56 Values for die block size calculation.

Similarly, where the relationship stated in the formula 4-5 holds true, we can calculate the height of the block by using the above formula 4-7, as:

$$h \geq \sqrt{\frac{1.5P}{S_B}\left(1-\frac{D}{1.5D_o}\right)} \tag{4-8}$$

With round openings supported by a square or rectangular block, the formula 4-8 for calculation of the height becomes:

$$h = \sqrt{\frac{1.5P}{S_B}} \tag{4-9}$$

Using the values referred to in Fig. 4-56*b*, calculate:

$$h \geq \sqrt{\frac{3P}{S_B}\left(\frac{\frac{b}{a}}{1+\frac{b^2}{a^2}}\right)} \tag{4-10}$$

The thrust force on the block can be calculated using formula 2-16, from Chap. 2.

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Occasionally an idea is expressed in the technical literature, stating that the designer should not make an effort to come up with dimensions of the hole-mounting locations, as the toolmaker should think up this part and make it work. It certainly is a debatable claim, as the toolmaker will surely need much longer to arrive at the right solution than a designer with a computer. Perhaps in some cases the toolmaker may even be forced to use the old trial-and-error procedure! Well—we all know that the designing process is much cheaper on paper than in steel.

4-3-2 Punch Plate

The punch plate is designed, dimensioned, and manufactured similarly to the die block. There is one difference though, when considering the view location: The die block is always viewed off its top surface, whereas the punch plate is usually seen from below.

For the purpose of accuracy, when using NC block-cutting equipment provision, both of these plates should be viewed and manufactured from the same location, from the top view of the die.

The punch plate, since it provides the support for all punch shanks, must be adequately thick but not in excess of what is necessary, in order not to increase the weight of a die. The correct thickness of this plate is in the range of 1.5D, with D being the diameter or the largest dimension of the biggest punch the plate should accommodate.

The work-related stresses of the stamping, forming, and other operations are equally distributed between the upper and lower portions of a die. However, when it comes to the upper section, or a punch plate, it is actually the punch that absorbs most of these stresses, while the plate is but marginally affected.

The terms "die block" and "punch plate" are often loosely applied to those plates that are holding dies and to those that are containing punches, respectively. Usually, the punches are located within the upper half of the die, while die bushings (or die buttons) are underneath in the lower blocks. Yet, there are instances where we pierce upwards as well (see Fig. 4-57). Such piercing (or blanking) is called *reverse piercing* or *reverse blanking* and in such a scenario the punch plate is located on the bottom of the die, while the die block is up on top. The choice of the punching orientation is governed by the arrangement of tooling within the die, by the manufacturing feasibility of all the cuts and formings, by the orientation of formed areas (i.e., forming up or forming down), plus by the requirements of that particular punching/blanking section.

In compound dies or in washer-producing dies, there are often punching arrangements capable of piercing down and up at the same time. This way, two cuts are achieved with each stroke of the press and with a single punch and die, as shown in Fig. 4-58. Here, while the first punch punches the smaller diameter, the second punch is blanking the outline of the part. Usually, in such situations, the produced parts are removed off the die face by pressurized air.

The mounting procedure of the punch plate to the die shoe is as shown in Fig. 4-59. Screws are inserted through the die shoe, where their heads are embedded. The upper backup plate has only clearance openings for them, and the tapped holes are going through the punch plate. This arrangement is the same whether a spring stripper is attached or not.

For dimensioning of punch plates, refer to the description for the die block, shown earlier in Fig. 4-55.

4-3-3 Backup Plates

Where used, both backup plates are made of hardened steel, $^3/_8$ in. (9.5 mm) thick for general work, $^1/_2$ in. (12.5 mm) thick for heavy-duty jobs.

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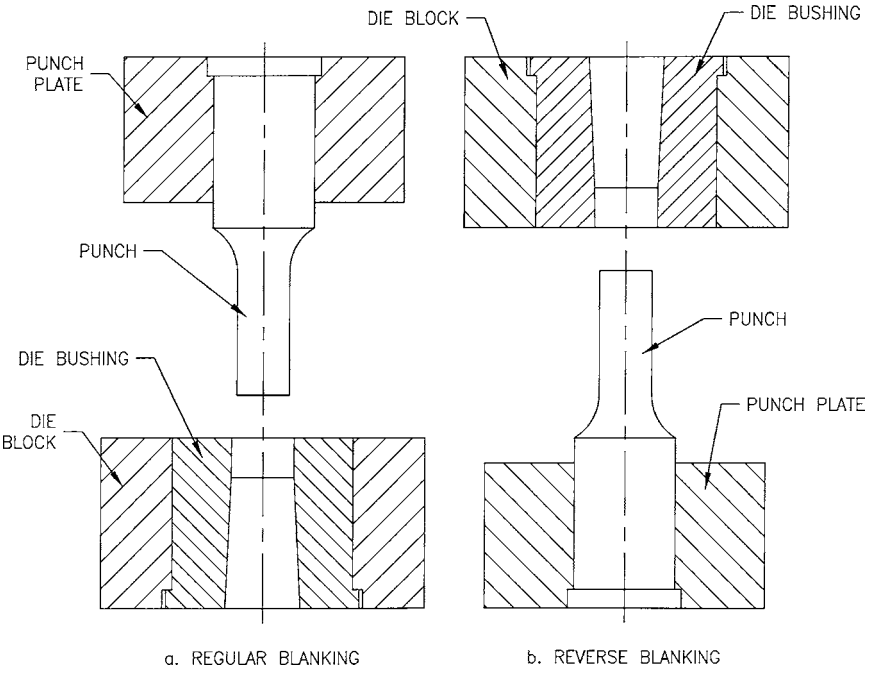

FIGURE 4-57 Regular and reverse punching.

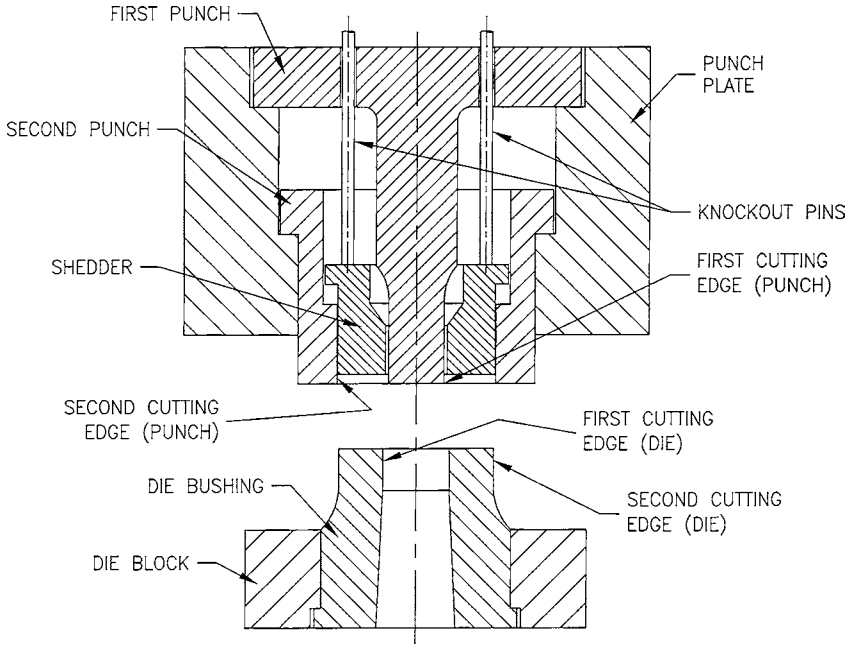

FIGURE 4-58 Double punching.

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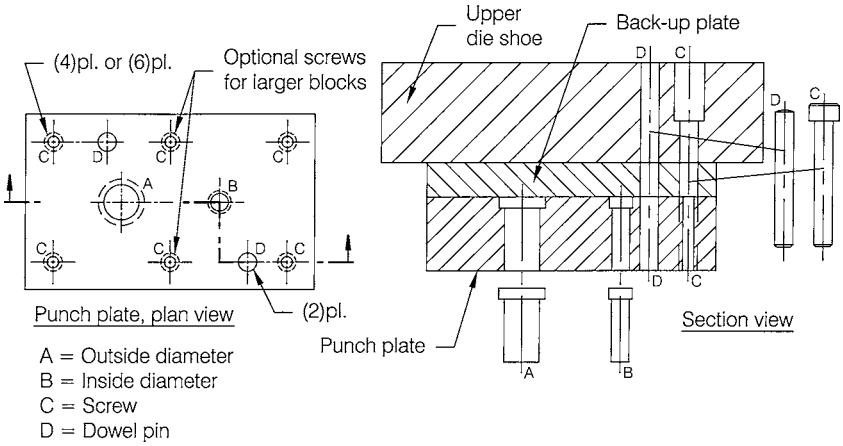

FIGURE 4-59 Punch plate section.

The hardness should be in the vicinity of 40 to 50 HRc, as a harder plate will not provide the proper support to the punches and/or dies and these may have a tendency to bounce off, or resonate. This in itself will certainly destroy them much sooner than planned. A2 steel is preferred to oil-hardened steels, which tend to be warped by the heat treatment, which affects their flatness.

Backup plates contain only clearance openings for screws and precision-finished openings for dowels. In slug-producing stations, however, they must have openings for the slug disposal; in blank-producing stations, such openings are used for parts' disposal.

4-4 MACHINING OF BLOCKS

All the material to be removed in order to produce holes in the blocks has to be drilled away in stages. It is not possible to take a $^5/_8$ in. (16 mm) diameter drill and drill a $^5/_8$ in. (16 mm) diameter opening in one pass. This may be done in wood or in other soft material, but certainly not in metal and especially not in tool steel.

4-4-1 Drilling of Holes

Every opening in a metal block must first be spot-drilled to establish its precise location for further processing. Following in a sequence, a rough drill is utilized, usually only slightly larger in size, let's say $^5/_{32}$ in. (4.0 mm) diameter. After this drill, another, larger drill (or subsequent drills) is used, to the point of almost finishing the diametral size of the opening, and then the jig bore reamer, a reamer, or a boring tool, or any other arrangement that provides a fine finish (Table 4-5).

With counterbores, the process is similar: first the spot drill, followed by a roughing drill and all the subsequent drills, all go through the whole block. Then comes the counterbore or end mill for the pocket, followed by a reamer or any other fine-finishing tool for the through hole.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

TABLE 4-5 Drilling Sequences for Various Openings

Hole dia	First drill	Second drill	Third drill	Fourth drill	Finishing tool
In inches					
1/8 (0.125)	Spot	3/32 (0.093)	–	–	0.1250 reamer
1/4 (0.250)	Spot	5/32 (0.156)	7/32 (0.218)	–	0.2500 reamer
5/16 (0.3125)	Spot	3/16 (0.187)	17/64 (0.265)	–	0.3125 reamer
3/8 (0.375)	Spot	3/16 (0.187)	9/32 (0.281)	11/32 (0.343)	0.3750 reamer
7/16 (0.4375)	Spot	3/16 (0.187)	9/32 (0.281)	13/32 (0.406)	0.4375 reamer
1/2 (0.500)	Spot	3/16 (0.187)	5/16 (0.312)	15/32 (0.468)	0.5000 reamer
In millimeters					
3.0	Spot	2.50	–	–	3.00 reamer
6.0	Spot	4.00	5.50	–	6.00 reamer
8.0	Spot	5.00	7.25	–	8.00 reamer
10.0	Spot	5.00	7.50	9.25	10.00 reamer
11.5	Spot	5.00	7.50	10.75	11.50 reamer
13.0	Spot	5.00	8.00	12.25	13.00 reamer

The sequence of counterboring operation is true with one exception: when using a subland drill for making clearance screw holes, counter-boring operation should be performed first.

With additional sizes, a fifth (later a sixth) drill may be added. The removal of material must be done in stages; otherwise the wear of tooling will result, along with poor-quality openings and their surface, overheated blocks, and subsequent tool breakage.

Drilling operation, once it exceeds the length of 2 to 3 times the hole diameter, is considered deep-hole drilling.

An important detail: In a sequence of operations, the last drill before the reamer should be –0.030 in. (–0.75 mm) per diameter smaller than the actual reamer's size. For counterbored holes, the difference between the last drill and the counterbore diameter should be 0.060 in. (1.5 mm) per diameter.

4-4-2 Feeds and Speeds

Feeds and speeds, useful for cutting of steel material, depend on the type of that material, its hardness, as well as the operation performed and the tool used.

Surface feed, or *tool feed*, is the rate at which the tool moves with every revolution of its spindle. In vertical drilling, surface feed is the movement of the tool coming down; in milling of pockets, it is the linear movement along a given path of work. Surface feed is usually specified in inches per minute or inches per revolution.

Cutting speed is actually the spindle speed, specified in either *revolutions per minute* (rpm) or *surface feet per minute* (sfpm).

Some basic cutting speeds are:

D2–D6 material	30 sfpm
O1 steel	45 sfpm
Low-carbon steel	65 sfpm

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Using the above values, different cutting processes should be limited to their percentages, as follows:

Drill	100%
Reamer	70%
Counterbore	110%
End mill	110%
Bore	200%

Where a need to recalculate surface speed in rpms into inches per revolution arises, the formula is

$$\text{rpm} = \frac{3.8 \times \text{sfpm}}{\text{tool dia.}} \tag{4-11}$$

and, subsequently,

$$\text{sfpm} = \frac{\pi \times \text{rpm} \times \text{tool dia.}}{12} \tag{4-12}$$

All surface feeds for fluted tooling should be checked for the true number of revolutions per each of the flutes, which should never be less than a minimum of

End mill	0.001 in. (0.03 mm) per rpm per 1 tooth
Reamer	0.001 in. (0.03 mm) per rpm per 1 tooth
Counterbore	0.0015 in. (0.04 mm) per rpm per 1 tooth

Spot drills' speeds and feeds should be in the vicinity of 480 rpm and 3.5 in./min (90 mm/min). Tap drill: 200 rpm, 12.5 in./min (320 mm/min). For countersink values, drill speeds and feeds should be used.

4-4-3 Miscellaneous Notes on Machining

Openings which are to be precisely finished, such as punch and die retaining holes and dowel pin holes, should be rough-cut and almost finished prior to heat treatment, leaving only about 0.008 in. (0.20 mm) per diameter to be removed afterward. Such a small amount of material should not present too great a problem, even when being removed off a hardened block. And yet many possible distortions, warping, deviations from straight line, and other defects caused by the heat treatment will be removed.

When drilling a block, operations should be grouped according to the tooling used. This way all spot drilling should be done to all openings at the same time. The same way, all the rough drilling should be performed together, followed by a sequence of finishing operations.

4-5 MOUNTING HARDWARE

All blocks are secured together with the aid of screws, the choice most often being socket head cap screws. With spring-and-bolt arrangements, shoulder screws are usually used to support the spring against misplacement or buckling with its shank, hold the spring-loaded block with its threaded portion, and control the length of the movement with the location of its head in the clearance pocket.

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METAL STAMPING DIES, THEIR CONSTRUCTION, AND ASSEMBLY

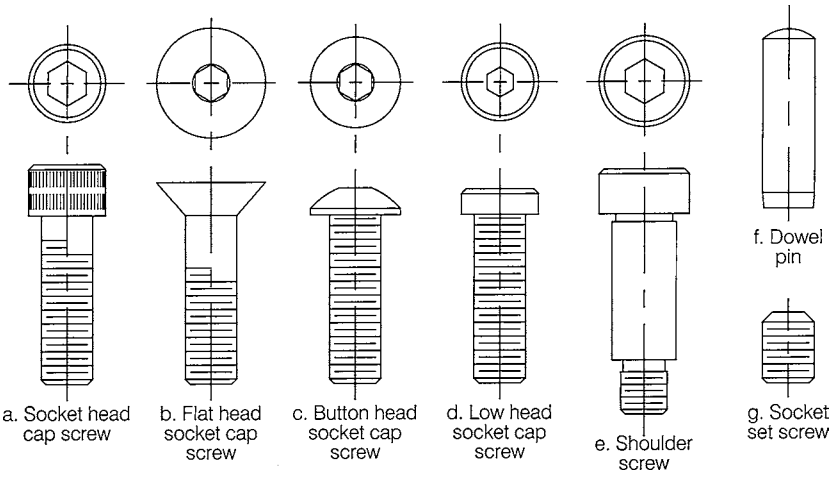
a. Socket head cap screw
b. Flat head socket cap screw
c. Button head socket cap screw
d. Low head socket cap screw
e. Shoulder screw
f. Dowel pin
g. Socket set screw

FIGURE 4-60 Mounting hardware.

Block mounting hardware (Fig. 4-60) should never be positioned too close to the edge of the block, as bulging of its side may occur, along with other distortions. The minimal recommended distance off the edge should be as shown in Table 4-6.

4-5-1 Attaching Several Blocks Together

When attaching several blocks together, screws must always be affixed to the last block of the whole sandwich, which must be the only one to have tapped openings (Fig. 4-61). All openings in blocks in between, no matter how many of them there may be, must be clearance holes.

Should the holes in all blocks be tapped instead, it will be impossible to align their threads against the threaded portion of the screw in assembly. This will create gaps between the blocks, with binding and breakage of the tapped areas, provided, of course, the blocks are assembled at all.

The clearance openings for the head of the socket head screws must be counterbored to a minimal depth of

$$\text{Screw head thickness} + \text{die life} + {}^{1}/_{16} \text{ in. } (1.5 \text{ mm})$$

TABLE 4-6 Minimum Distance Between the Center of a Screw and the Edge of the Mounting Block

	Material of the mounting block	
Type of installation	Aluminum, CRS	Other alloys
Socket head cap screw	1.7 diameters*	2 diameters*
Flat head socket cap screw	2 diameters*	2.5 diameters*

*Add diametral tolerance of the screw to the amount shown.

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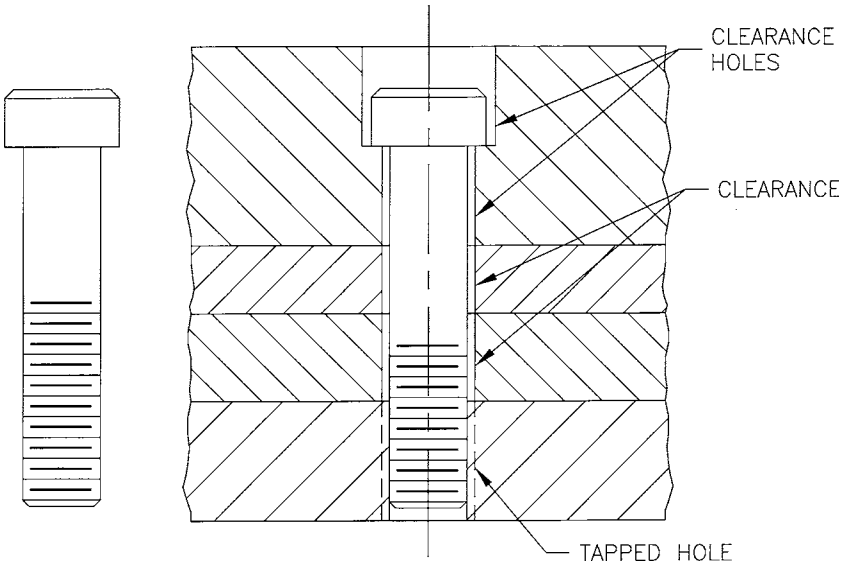

FIGURE 4-61 Screw-mounting of several blocks.

4-5-2 Length of Thread Needed

A screw needs to engage at least $2\frac{1}{2}$ of its threads to be considered holding the object. However, the designer need not be limited by such a claim, especially where enough space in blocks is provided for a longer threaded portion and where a few more turns of a wrench are not out of place.

The proven and acceptable lengths of a threaded portion should be the greater of these values:

UNC threads Screw dia. + $\frac{1}{2}$ in. (12.5 mm) or $\frac{1}{2}$ (screw length)

UNF threads $1\frac{1}{2}$ (screw dia.) + $\frac{1}{2}$ in. (12.5 mm) or $\frac{3}{8}$ (screw length)

Tap drills, which always precede the tapping operation in metal machining (in plastic or wood, self-cutting screws are often used), should be used to drill the opening through the whole thickness of the block whenever possible. This procedure should be considered even in cases where the tapped portion of the hole is much shorter than the block itself.

The reason for this claim is the difficulty of producing a blind hole in metal, where chips often get locked inside and obstruct the performance of the drill and where air pockets may be encountered to further jeopardize the work.

4-5-3 Dowel Pins' Assembly (Fig. 4-62)

Dowel pins are used for securing the blocks in a fixed, precise position relative to each other. Screws are but a means of attachment, whereas dowels provide for all the alignment needed.

For that reason, dowel pins must run through the whole length of the assembly of blocks, and in each of them the holes must be precision-finished. However, the dowels do not have to be surface-to-surface long, as a precaution against their protruding through one end or the other.

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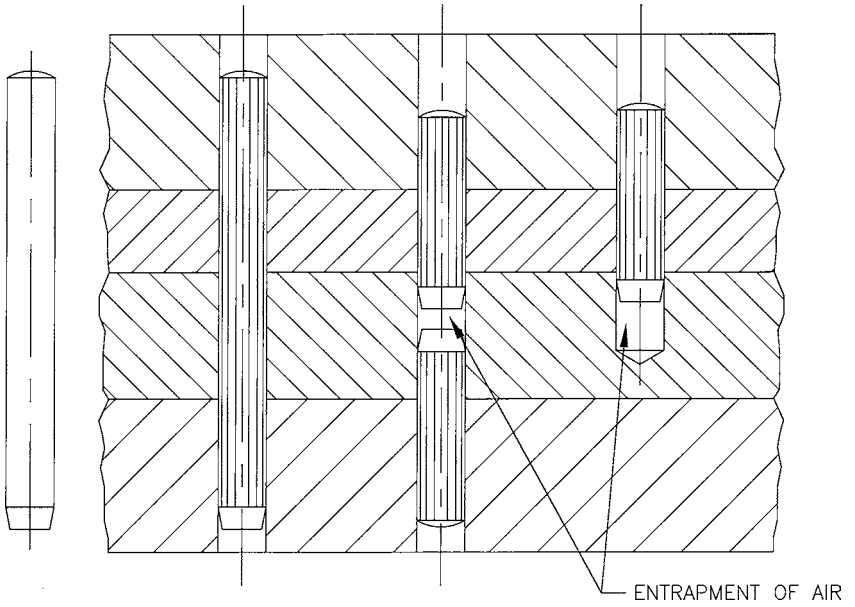

FIGURE 4-62 Dowel pin assembly.

At least all dowel-pin openings in the two extreme blocks must be press-fit. The holes through the blocks in between may sometimes be only tight-fit. However, this consideration depends on the type of die, its function, and the common practice of that particular shop.

When looking at a block from the top view, the dowel pin's location should be at two extreme ends of the block to provide the broadest range of application. As already mentioned, dowels (and perhaps screws as well) should be spaced unequally, so that no block can be turned around and assembled the wrong way.

As a precaution, dowels should never be assembled into a blind hole, for a lack of ventilation at the bottom of it would create an air pocket, impairing the dowel's assembly and stability of performance. For common dowel pin sizes see Table 4-7.

TABLE 4-7 Basic Dowel Pin Sizes

Nominal dia.		Actual dia.		Hole size	
				+0.0000	
in.	mm	±0.0001	h11	−0.0003	H7
1/8 (0.125)	2	0.1252	2.00	0.1250	2.00
3/16 (0.1875)	3	0.1877	3.00	0.1875	3.00
1/4 (0.250)	4	0.2502	4.00	0.2500	4.00
5/16 (0.3125)	5	0.3127	5.00	0.3125	5.00
3/8 (0.375)	6	0.3752	6.00	0.3750	6.00
7/16 (0.4375)	8	0.4377	8.00	0.4375	8.00
	10		10.00		10.00
	12		12.00		12.00

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4-6 JIGS AND FIXTURES

Jigs and fixtures can be considered a part of die building and die making, and almost every toolmaker displays a distinct ingenuity in devising and using them. Most often, jigs and fixtures are used to clamp down various parts, hold down the blocks, and so on. The most widely used types of clamps are shown in Fig. 4-63.

A jig is actually a clamping device, holding a part in the position where it can be drilled, cut, formed, or otherwise altered. The jig may be assembled from all kinds of adjustable elements, but it must have a positive nesting arrangement, where the part may be placed and correctly oriented against the tool.

A drill jig should be made to stand on four legs. To leave the jig arrangement sitting flat on the table is not advisable, as the chips will have no place to go, while the table, acting like a plate, will make it difficult to orient the part against the tool.

Every jig drill should be received in a bushing, to guide its movement and protect it from breakage. Drill bushings should be made of hardened tool steel. They do not have to be contained in a block; clamping them in a proper location will serve the purpose as well.

There are many types of jigs: indexing jigs, vise jigs, plate jigs, universal jigs, and tumbling jigs.

Some other clamping and fixturing arrangements included here should be studied for their versatility and genuineness (Fig. 4-64). Most of these combinations were arrived at through many years of experience of many toolmakers, engineers, and designers.

The *A* method of fixturing shown in Fig. 4-64 displays a continuous spiral rise similar to that used on automatic lathes. Such a cam will lock securely at any point of its location and remain locked even during cutting. A 90° movement of the handle is quite adequate, but if a provision for greater material thickness is required, a 180° angle of movement would be more appropriate.

In the cross section of a wedge clamp, shown in Fig. 4-65*a*, the push rod and a hand knob are connected to the horizontal mechanism of a wedge. A vertical stud, sliding in a steel bushing, leans against the surface of the wedge, and it is moved up and down by the horizontal movement of the whole part.

An alternative device, equipped with a spring plunger, is shown in Fig. 4-65*b*. Here a large hatlike top protects the plunger from being cut into. Air vents are provided at *A* and *B* locations.

A strap, shown in Fig. 4-66*a*, is attached to the workpiece by two bolts. The whole assembly may experience quite a strain if the work surface is not flat. A pressure pad with rounded end is used to alleviate this problem. Also spherical-end washers and slots in the

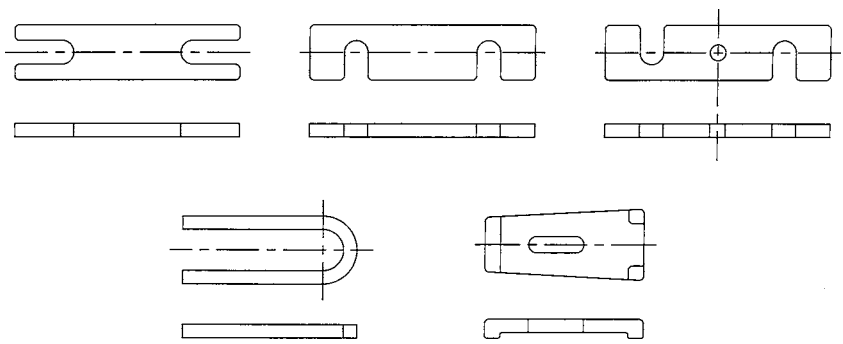

FIGURE 4-63 Clamps used in fixturing of work.

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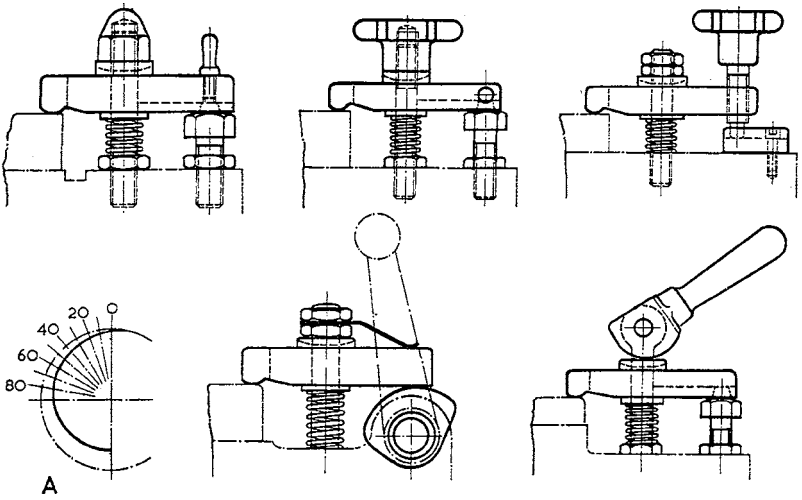

FIGURE 4-64 Typical clamping devices used for jigs and fixtures. (From: *H.C. Town,* "Technology of the Machine Shop," *1951. Published by Longmans, Green & Co.*)

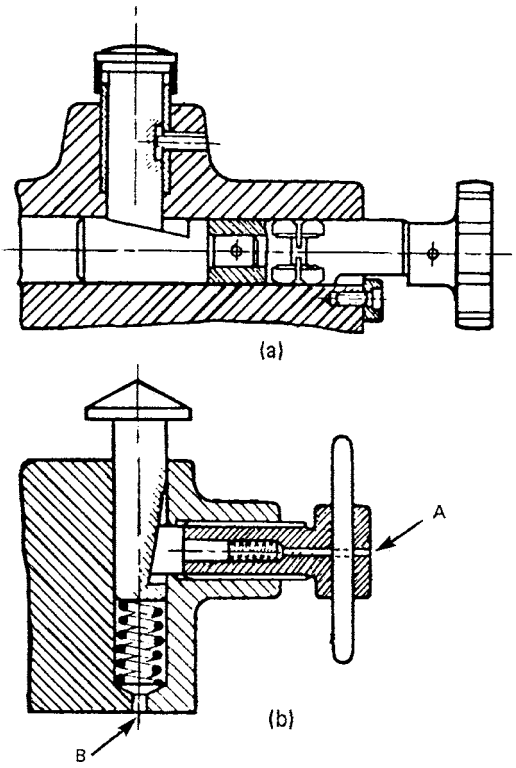

FIGURE 4-65 (a) Wedge clamp; (b) Supporting plunger. (From: *H.C. Town*, "Technology of the Machine Shop," *1951. Published by Longmans, Green & Co.*)

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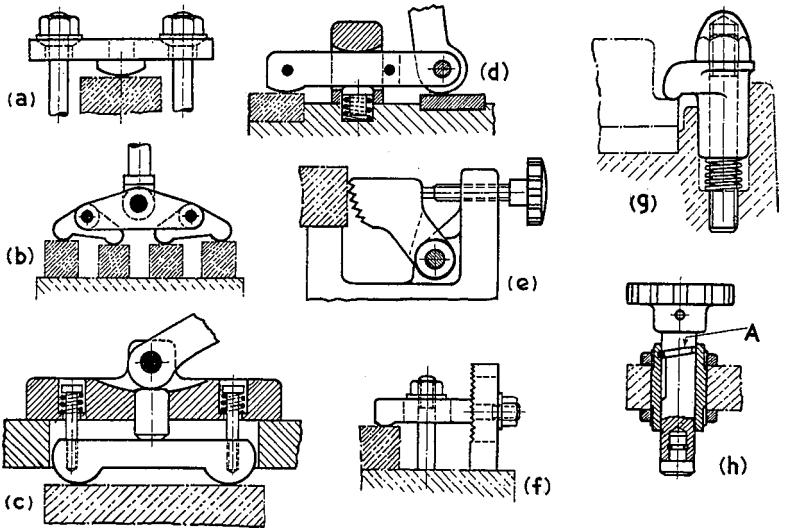

FIGURE 4-66 Equalizing and other rapid clamping devices. (From: *H.C. Town*, "Technology of the Machine Shop," *1951. Published by Longmans, Green & Co.*)

clamp may provide for the free movement, while not impairing its function. The disadvantage of such a clamping idea is that if a pressure is applied at a single point only, the working surface beneath may be marred.

A better arrangement is shown in Fig. 4-66*c*, where the pressure generated by the cam is transferred to the central stud, which subsequently presses against a strap with only two points of contact with the work surface.

The arrangement in Fig. 4-66*b* has a central rod mounted to a set of pivoted levers, which provide for the equal distribution of the vertical type of pressure.

A cam-operated sliding lever clamp is pictured in Fig. 4-66*d*. Here the centrally located support presses the arm against the upper surface of the guiding slot. Locking of the assembly is achieved through the movement of a cam-actuated lever arm.

Figure 4-66*e* has a serrated portion of the clamp leaning against the workpiece and tightened by a hand knob. The angle of serrations is of essence here, being established at 45°. With such an arrangement, the vibrations of the work process will not release the grip but rather push downward on the serrated jaw.

Figure 4-66*f* is a commercially available Hamber clamp. The heel-supporting piece is provided with accurately machined serrations, which allow for a rapid adjustment with variation in height.

A vertical clamp, shown in Fig. 4-66*g*, holds the workpiece by a pressure of its nose. The advantage of such clamping is the small amount of space it demands.

The benefit of two-way clamping (or multiple clamping) is the fact that even though it banks on two or more points, its clamping actuation is done from one position only. Some examples of this type of device are shown in Figs. 4-67 and 4-68. Additional clamping ideas are included in Fig. 4-69.

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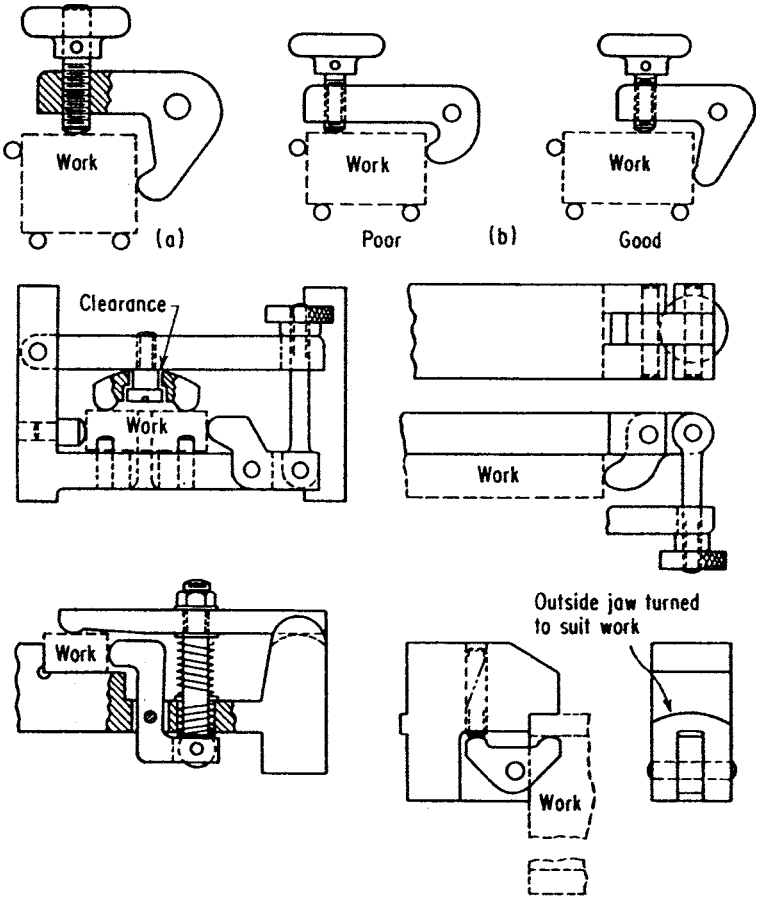

FIGURE 4-67 Two-point clamping devices. (From: *Frank W. Wilson,* "Handbook of Fixture Design," *1962. Reprinted with permission from The McGraw-Hill Companies.*)

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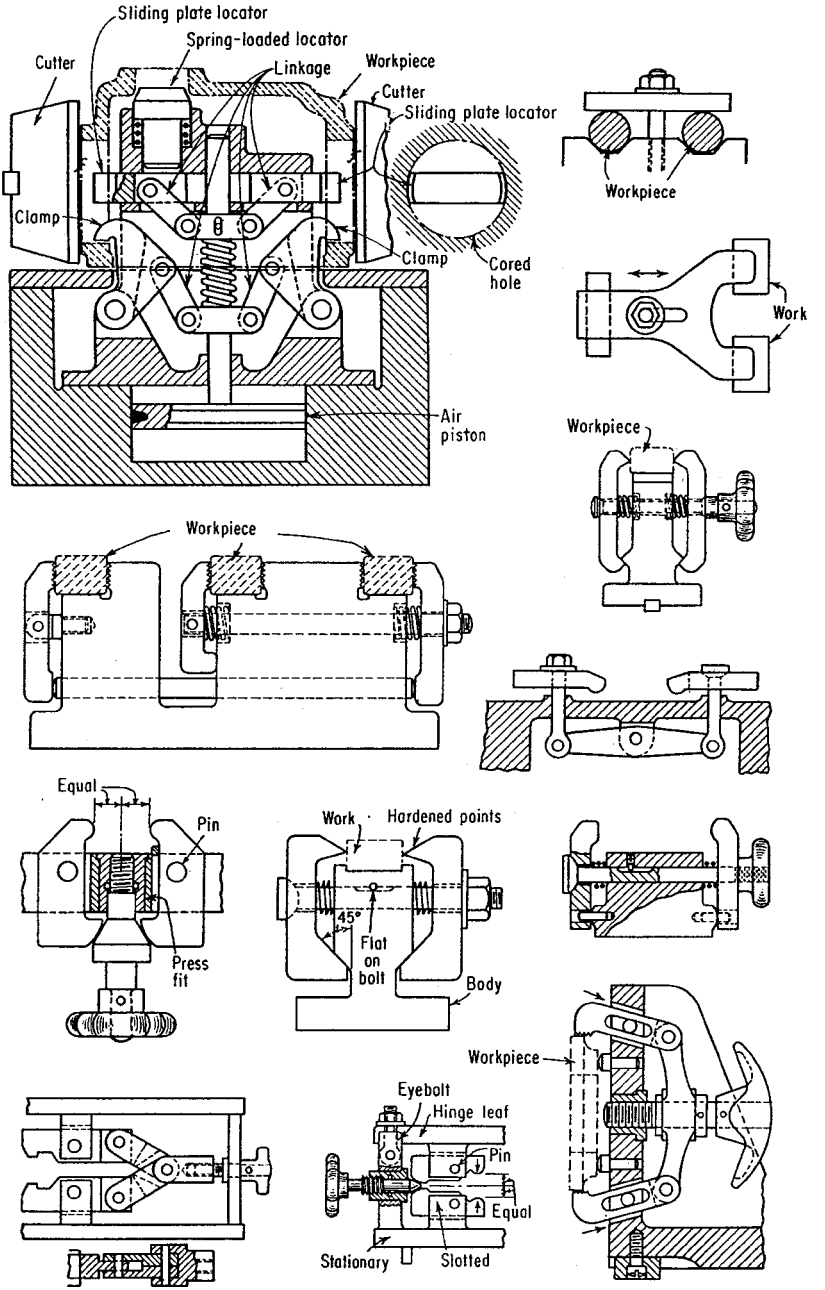

FIGURE 4-68 Centrally actuated clamping devices. (From: *Frank W. Wilson*, "Handbook of Fixture Design," *1962. Reprinted with permission from The McGraw-Hill Companies.*)

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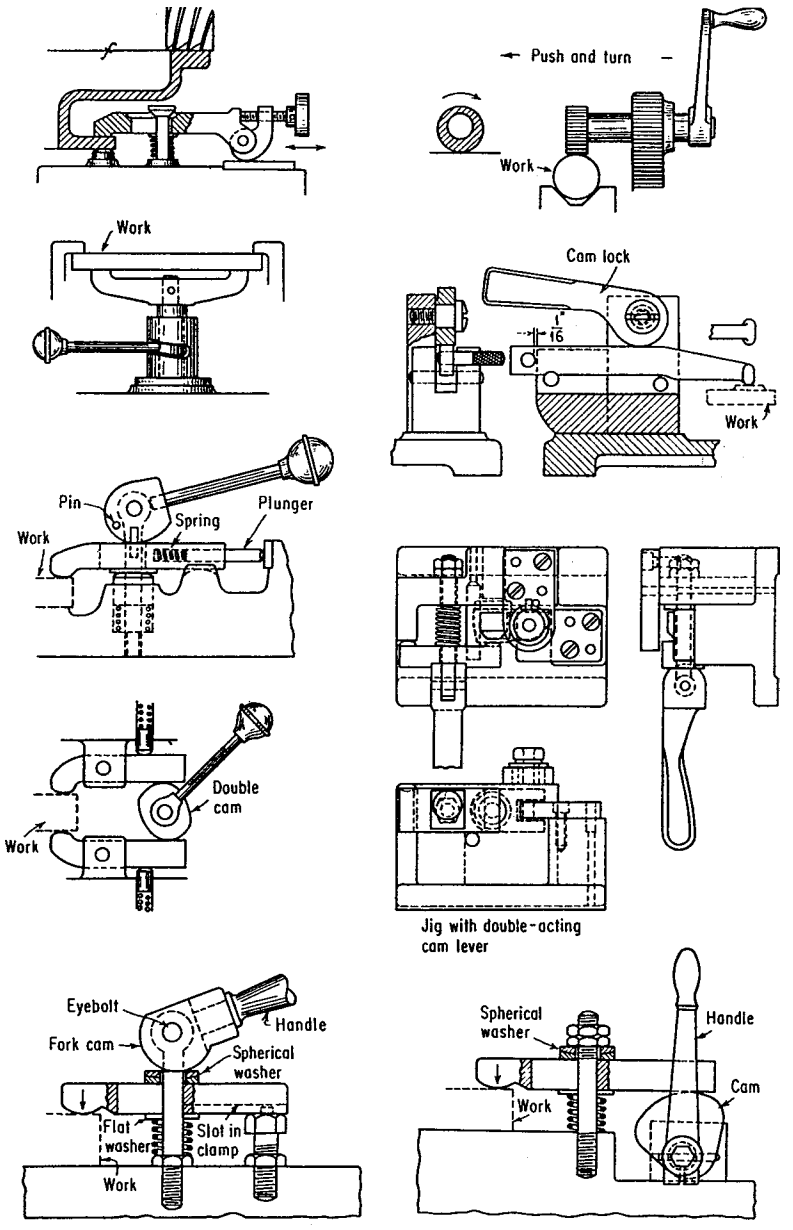

FIGURE 4-69 Types of cam-actuated clamps. (From: *Frank W. Wilson*, "Handbook of Fixture Design," *1962. Reprinted with permission from The McGraw-Hill Companies.*)

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CHAPTER 5
METALWORKING MACHINERY

5-1 METALWORKING MACHINERY

The function of all metalworking machinery can be described as that of a force-producing mechanism which delivers its required output in a certain period of time with a predetermined amount of accuracy. The amount of the force and its method of application are not always consistent. Rolling machines apply a constant and uniform force toward a bar of steel, while drop hammers produce a single blow in a unit of time. The same amount of force may be divided into many smaller hits and distributed over a longer time period by the pneumatic hammer.

When classifying metalworking machinery according to the way it functions, there are two basic types of distinction:

- *Machines with linear movement of their tools*, such as presses, certain rolling machines, wire- and bar-drawing, and stretching machines
- *Machines utilizing nonlinear movement of tooling*, such as bending and rolling machines, the rolling application being either longitudinal or cross rolling in type

In further evaluation of metalworking machinery, the scope of this problem is restricted to presses.

5-1-1 Presses, According to Their Function

Presses can be evaluated with regard to their function as

- *Energy-producing machines*, with the application of this energy being abrupt and instantaneous. All the machine's energy storage is depleted at the end of its work cycle. Such machines are hammers, which use a "free fall" principle as a basis of their function. However, sometimes their efficiency is increased by an addition of steam or pressurized air. The hammers' energy source is temporarily disconnected at the time the ram is released for an operating cycle, which consists of its falling down on the workpiece.
- *Force-producing machines*, which operate by generating a considerable amount of force, independent of the position of the ram. Hydraulic machinery is the main representative of this category.
- *Stroke-controlled machines*, or mechanical presses, the function of which depends on the movement and location of the ram. During the work cycle, the ram is always in contact with the source of its power. These presses can be further divided as

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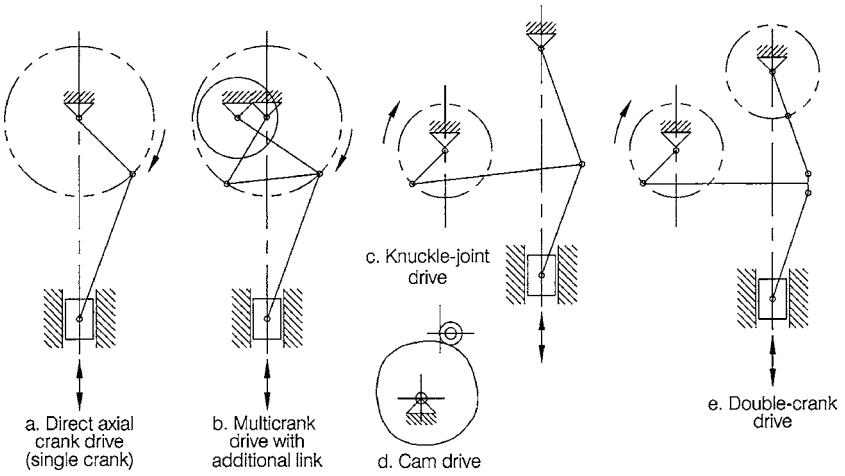
a. Direct axial crank drive (single crank)
b. Multicrank drive with additional link
c. Knuckle-joint drive
d. Cam drive
e. Double-crank drive

FIGURE 5-1 Various types of press drives.

- Presses driven by a crank or eccentric drive. *Simple crank drives* are the most commonly used types, with *extended crank drives* in knuckle-joint presses.
- Presses driven by a cam. *Cam-driven systems* are used in presses with less tonnage.

Each of these groups has certain advantages and disadvantages closely connected with the type of process they represent. For example, hydraulic presses have fewer operating parts, which brings the cost of their repairs down. However, should these machines be in need of any repair, such a procedure will be very demanding. With mechanical presses their breakdowns are visually detectable, but a complete knowledge of the circuit is required to find a problem within a hydraulic system. Also the tolerance range of hydraulics is not as impressive as that of mechanical presses, with the latter group also being faster. Fortunately, each type's usefulness is given by the type of its applications, and that's where their function, along with its advantages and drawbacks, fits. (See Figs. 5-1 through 5-6.)

5-1-2 Presses, According to Their Energy Supply

There are several categories of machines, their main difference being in the working media they use. We recognize:

- *Mechanical presses*, where the work force is supplied by some mechanical means, such as a cam or lever
- *Hydraulic presses*, utilizing the pressure of water or other fluid media
- *Steam presses*, using pressurized steam
- *Pneumatic presses*, operating with the aid of pressurized air
- *Electromagnetic presses*, where the ram is moved by the application of electromagnetic force

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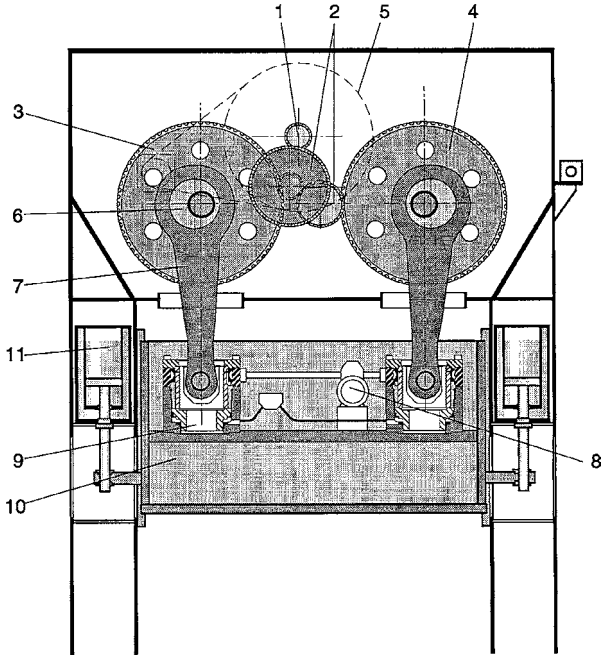

FIGURE 5-2 Press drive principle: (1) Main shaft. (2) Pinion. (3) Gear. (4) Gear. (5) Driving belt. (6) Eccentric connection. (7) Connection link. (8) Slide adjustment. (9) Ram-retaining assembly. (10) Ram. (11) Counterweight. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

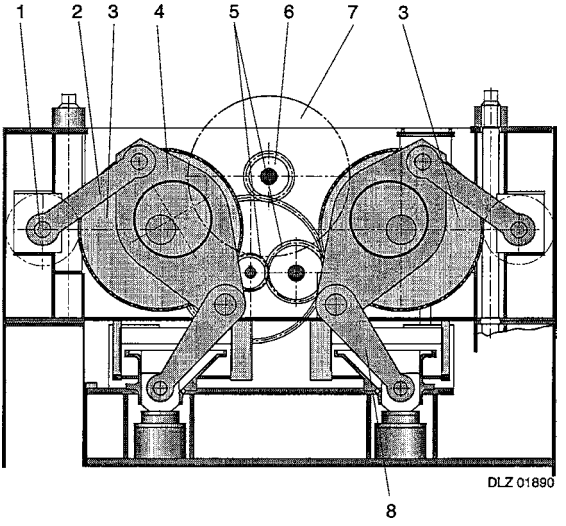

FIGURE 5-3 Joint mechanism: (1) Fixed point. (2) Connecting link. (3) Eccenter. (4) Rocker. (5) Gear assembly. (6) Main shaft. (7) Flywheel. (8) Ram connection. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

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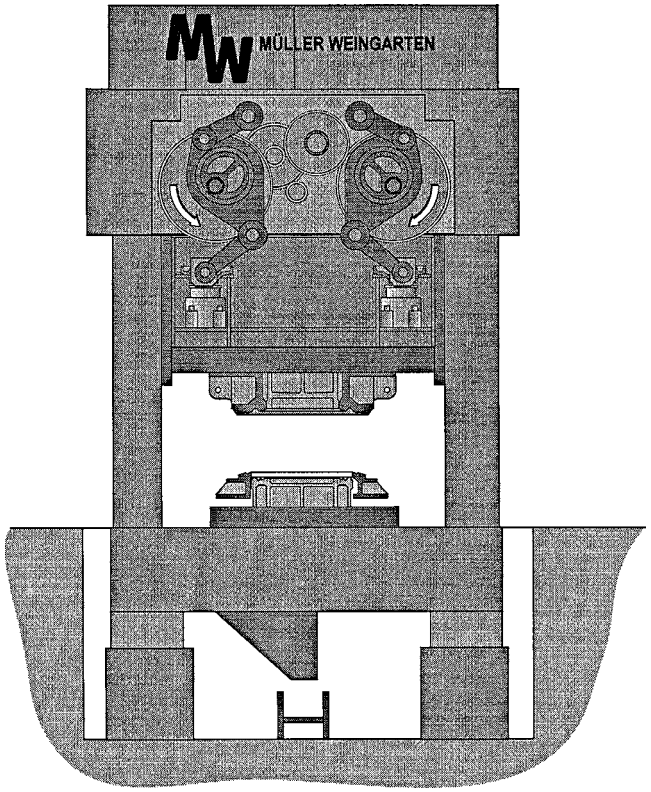

FIGURE 5-4 Double-column press. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

5-1-3 Presses, According to Their Construction

Variations due to the construction of presses allow for the distinction, based on types of press frames, as:

- C-frame presses or gap-frame
- Closed-frame presses or O-frame

C-frame construction is often used with smaller-capacity presses. Their main advantage lies in the easily accessible work area, which accounts for shorter setup and adjustment times. This advantage is perhaps outweighed by their faults, mostly attributable to the shape of their frame, whose construction is likely to suffer from deflection under load. However, in current machine building, heavy tie rods and other reinforcements are used to secure the machine's sturdiness and accuracy.

These two groups of frame-dependent classification can be further divided into presses with a single column, double column, and pillar-supported presses (Fig. 5-7).

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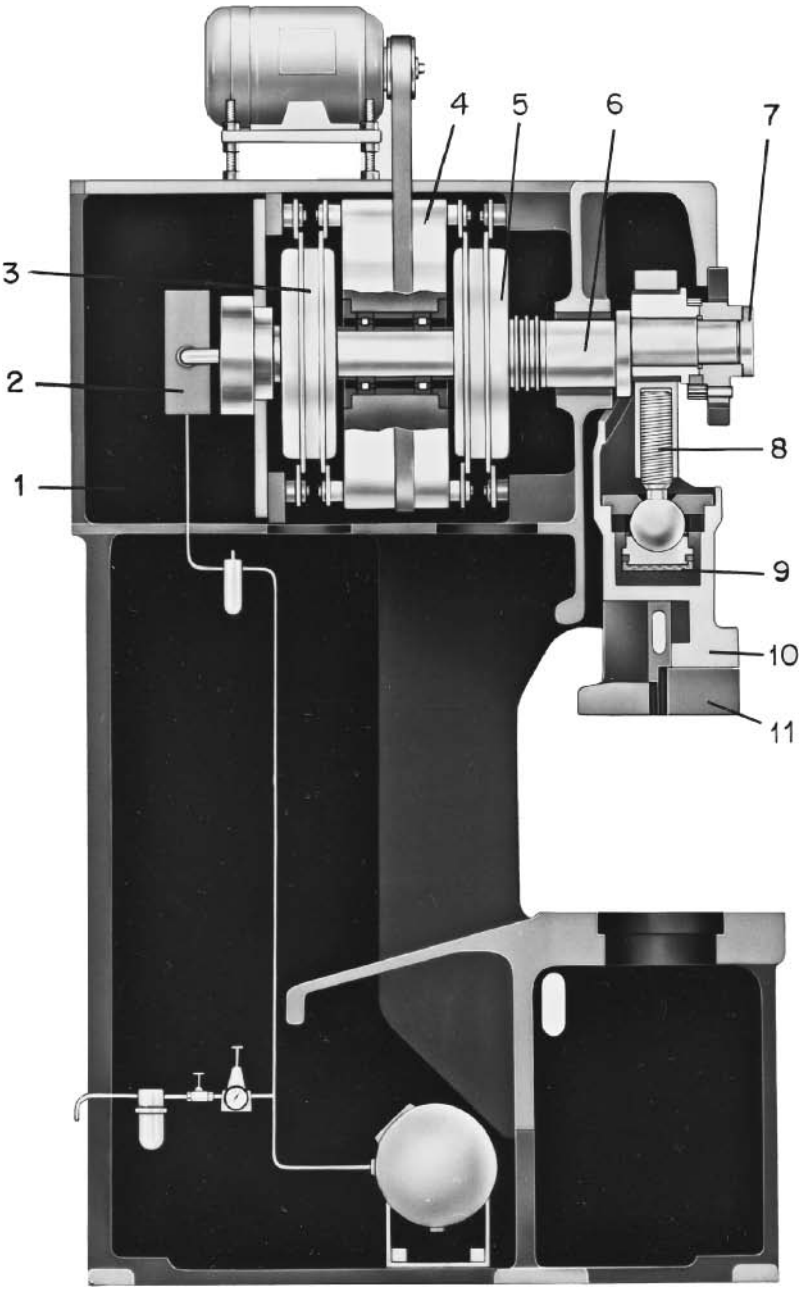

FIGURE 5-5 Sectional view of the press mechanism without reduction gears: (1) Frame. (2) Control valve. (3) Clutch and brake. (4) Flywheel. (5) Clutch and brake. (6) Eccentric shaft. (7) Slide stroke adjustment. (8) Slide adjustment. (9) Overload safety device. (10) Slide. (11) Clamping block. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

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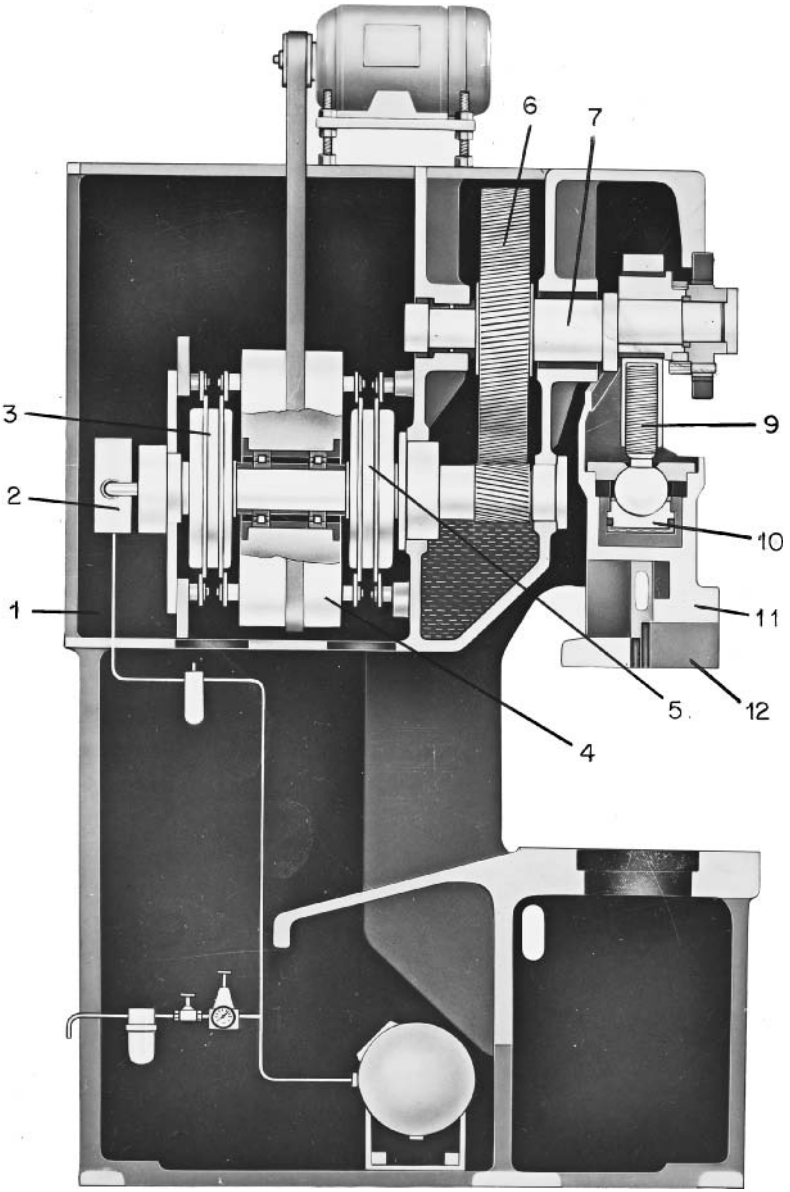

FIGURE 5-6 Sectional view of the press mechanism with reduction gears: (1) Frame. (2) Control valve. (3) Clutch and brake. (4) Flywheel. (5) Clutch and brake. (6) Reduction gearing. (7) Eccentric shaft. (8) Slide stroke adjustment. (9) Slide adjustment. (10) Overload safety device. (11) Slide. (12) Clamping block. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

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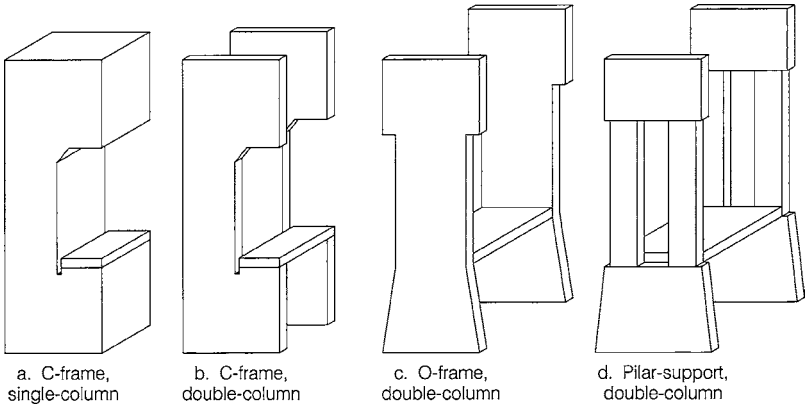

FIGURE 5-7 Press frame types.

Additionally, according to their width-to-height ratio and to the deviation from vertical, presses can be further categorized as vertical and horizontal presses, inclined or inclinable presses, and adjustable-bed presses (Fig. 5-8). Figures 5-9 through 5-14 show various presses. Figure 5-15 shows various drive systems.

The so-called "straight-side" press frames consists of a press bed, which supports the bolster, the crown, two uprights, and the ram (i.e., slide). The uprights form a connection between the crown and the bed by either being bolted and keyed together, or by tie rods. Straight-side presses are usually more stiff than gap-frame presses. They additionally do not suffer from angular deflection, and where vertical deflection under a load is present, it is almost symmetrical if their loading is symmetrical too. For these reasons, straight-side presses usually endanger the punch and die alignment the least.

Another aspect, which affects unfavorably the gap-frame presses equipped with tie rods is the misalignment caused by the tie rods themselves. These connecting links, in order to provide the press with the stability and resistance to deflection it needs, have to be tightened so much that the whole press frame becomes subject to preload. This condition, naturally,

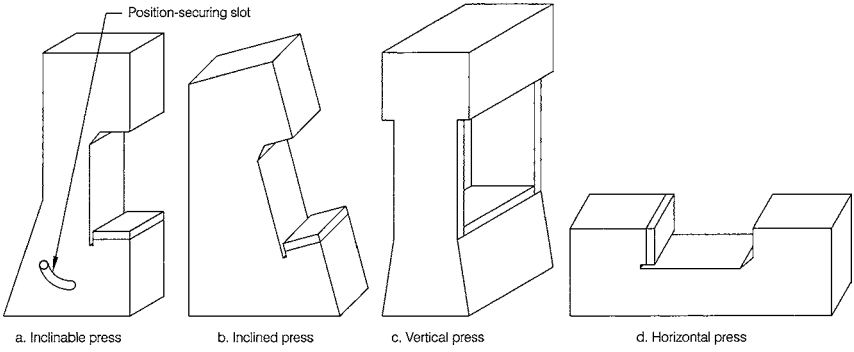

FIGURE 5-8 Presses with respect to the horizontal.

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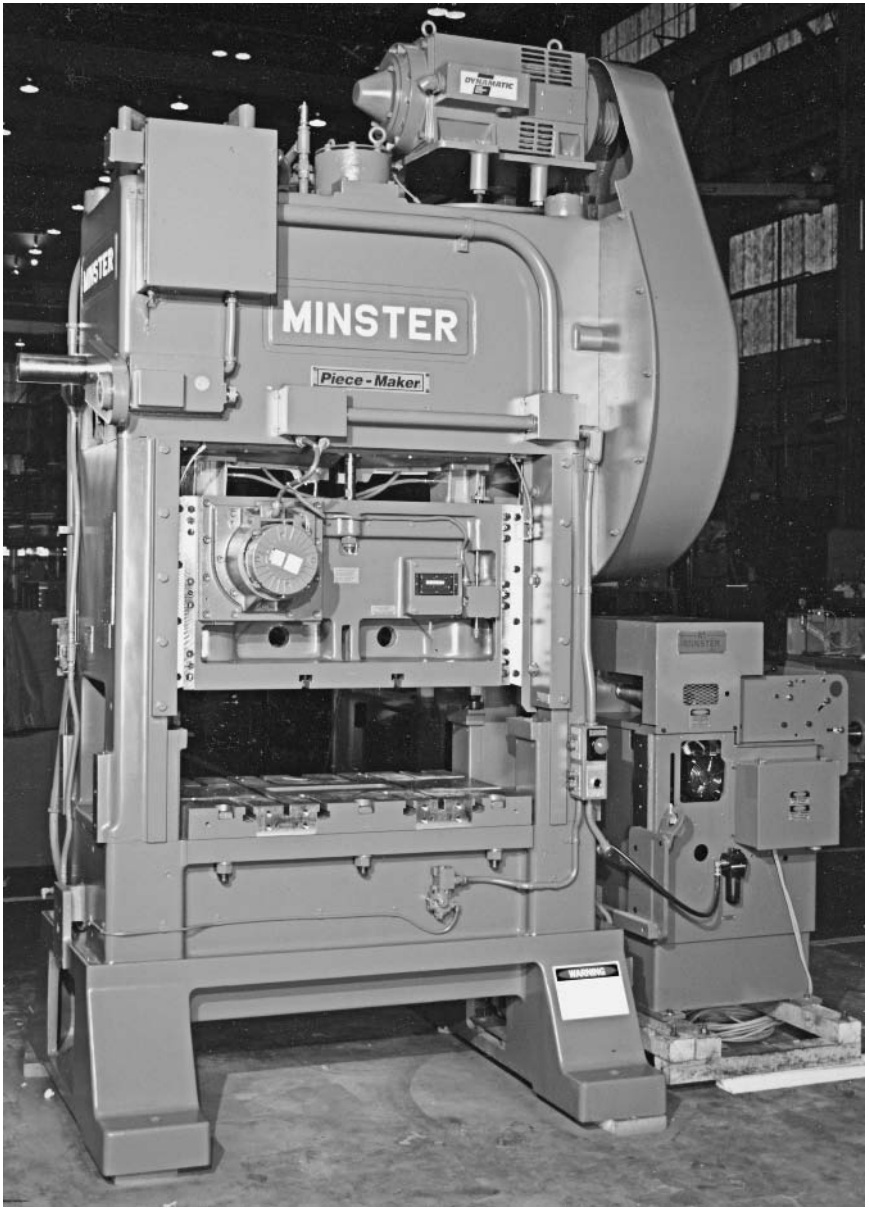

FIGURE 5-9 Straight-side, high-speed automatic press. Frame: high-tensile strength cast iron, four-piece tie rod construction. Crankshaft: full eccentric, forged alloy steel. Eight point gibbing. Flywheel or geared. 30–200 tons capacity, 60–500 strokes per minute. (*Reprinted with permission from Minster Machine Co., Ohio.*)

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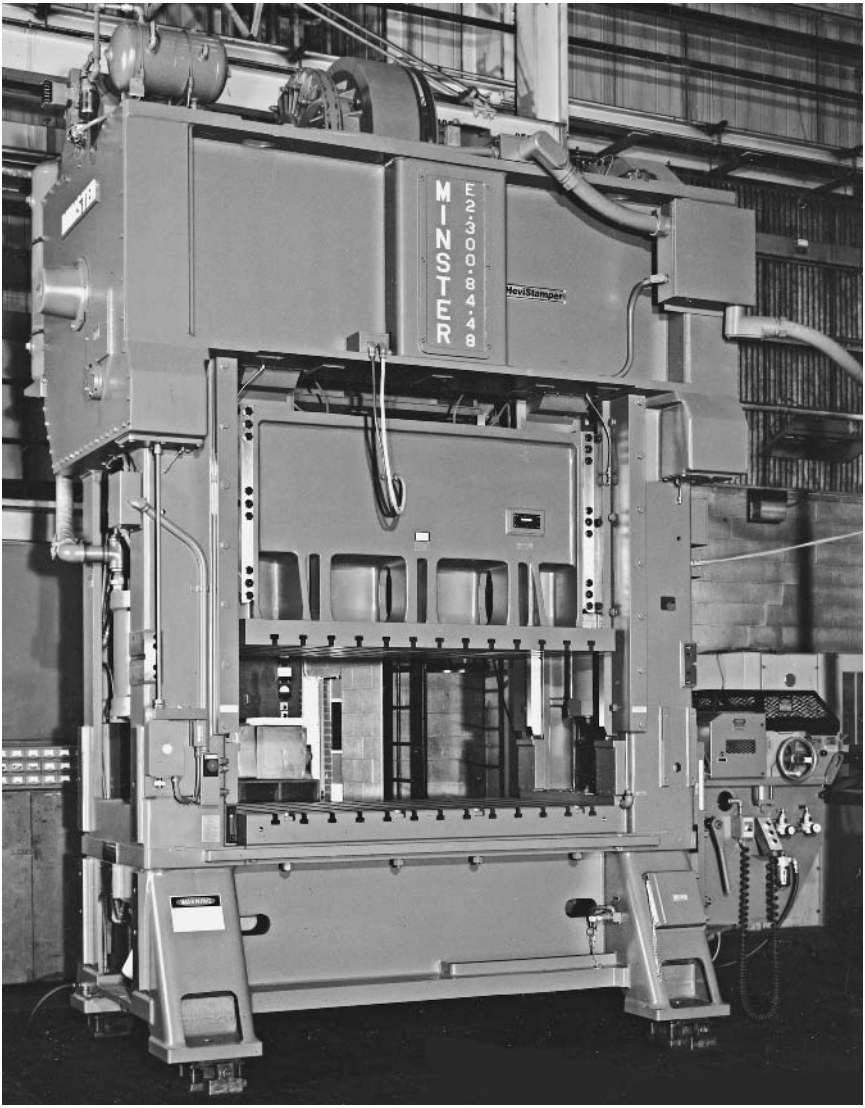

FIGURE 5-10 Straight-side press. Frame: four-piece tie rod construction. Crankshaft: full eccentric, made of forged alloy steel. Square gibs guide the slide front to back and left to right. Single geared twin drive. 200–1000 tons capacity, up to 150 strokes per minute. (*Reprinted with permission from Minster Machine Co., Ohio.*)

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FIGURE 5-11 C-frame hydraulic press. Frame: welded. Capacity: 250 to 2500 kN. Working speed up to 8–38 mm/sec. Maximum pressure 21 to 24.5 MPa. Electrohydraulic controls by Mannesmann Rexroth. (*Reprinted with permission from OSTROJ, Opava, Czech Republic.*)

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FIGURE 5-12 Open-front power press. Notice the heavy tie rods. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

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FIGURE 5-13 Verson Model ETF-48-9-10TA Electronic Tri-Axis Transfer System with full programmable servo control for up to 48 in. Transfer stroke, 9 in. Clamp stroke, and 10 in. Lift. Motion parameters and die parameters, including the number of finger sensing and die sensing stations, can be programmed in the "die library menu" and displayed on the Smart Screen operator interface. (*Reprinted with permission from Verson and Danly Division of Enprotech Mechanical Services, Inc., Lansing, MI.*)

forces the ram and the bolster out of parallel which may endanger the tooling along with the press. The type of press drive used may introduce an additional variation. Figure 5-17 shows a *single-point system of drives*, in which the rod connecting the ram to the crankshaft is only one; a *two-point system*, in which the ram is tied to the crankshaft in two places; and a *four-point system* of drive variation, tied at four places. Most often the driving force is delivered from the upper area of the press, but sometimes even bottom-located driving systems may be used.

5-2 PARTS OF THE PRESS

Presses consist of several essential components, assembled within the mass of their frames. Years ago, the presses were simple and straightforward, but also limited in their function. Today's presses contain electronic controls, including programming capacities, and altogether, they can work miracles. These previously rigid and unyielding machines can now be set and adjusted to provide for any whim and fancy of a demanding toolmaker, shop supervisor, or engineer.

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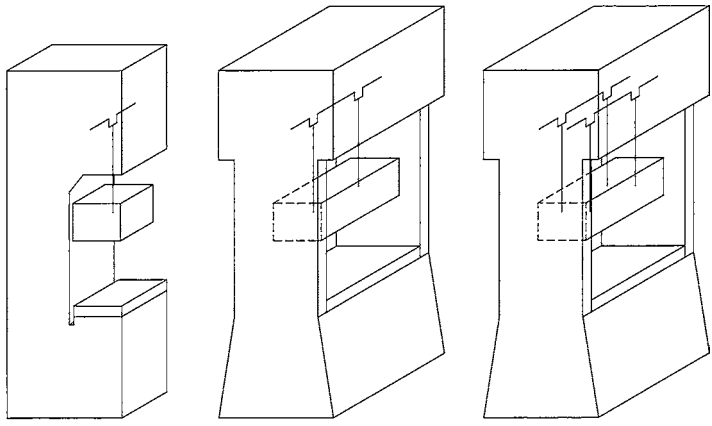
FIGURE 5-14 Danly 2500 ton Automotive Transfer Press, model S4-2500-252-108TF upgraded with a Verson Electronic tri-axis transfer system, model ETF 45-9-8TA for transferring parts up to 45 in. between stations at up to 20 strokes per minute. (*Reprinted with permission from Verson and Danly Division of Enprotech Mechanical Services, Inc., Lansing, MI.*)



a. Single-point drive

b. Two-point drive

c. Four-point drive

FIGURE 5-15 Drive systems.

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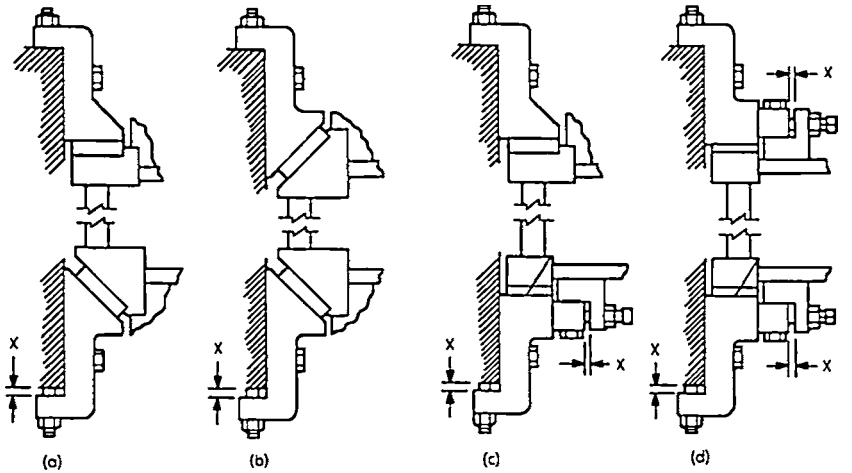

FIGURE 5-16 Various configurations of gibbing used with the box-type guiding system: (a) flat rear gib and 45° front gib. (b) front and rear 45° gibs, (c) and (d) square gibbing. Allowance for adjustment is indicated by X. (*Reprinted with permission of the Society of Manufacturing Engineers, Tool and Manufacturing Engineering Handbook, Fourth Edition, Volume 2, Forming, Copyright 1984.*)

5-2-1 Press Frame

The frame of the press must be sturdy and rigid in construction, which alone influences the functional accuracy of the machine. With weak frames, the deflection and later deformation of the mounting surfaces may occur, producing a subsequent misalignment of main parts, and possible breakage.

The sturdier and more rigid and stiff the frame is, the less the press mechanisms are affected by their own function.

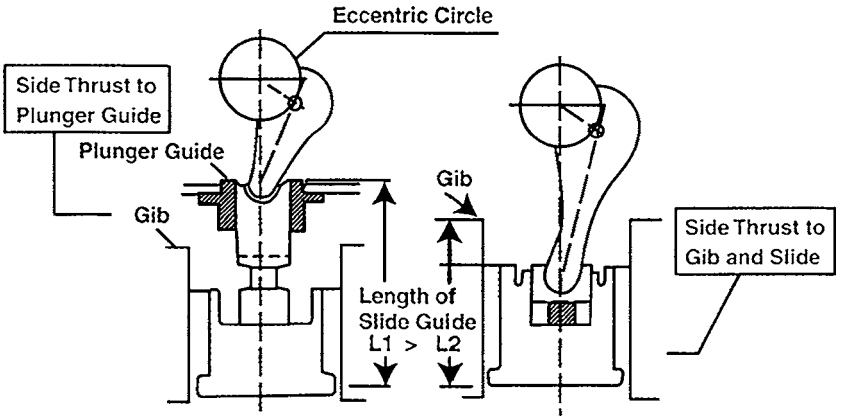

FIGURE 5-17 Plunger-guided slide design. (From: *The FABRICATOR®, February 2000, page 77, by James Landowski. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

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The material of the frame is another aspect to be evaluated, for cast iron will succumb to deformation more readily than steel, since its modulus of elasticity is lower.

The best type of frame for press work is the fully enclosed O-type with the fewest openings in the sides and supports. All its flanges and openings should be provided with well-rounded corners, with no sharp or abrupt lines or connections of any kind.

Press frames are either cast or welded together from segments. Cast frames are used for smaller presses, their sides sometimes being reinforced with additional plates or tie rods to increase their sturdiness in operation.

Welded frames may be produced either as a group of various assemblies welded together to form a single mass or may consist of various segments welded together but finally attached to each other by other means, the most common method of attachment being that of anchoring with ties, rods, and plates.

5-2-2 Bolster Plate

Bolster plate, sometimes called *press table*, is positioned on top of the press bed. It is a heavy plate, ribbed with T slots (to receive T bolts in the assembly of a die), precision-aligned to the frame with dowel pins.

5-2-3 Ram

The ram, sometimes also called the *slide*, is the work-delivering part of the press, sliding up and down, as powered by the driving elements of the machinery.

Proper guidance of the ram, as it moves up and down, is provided by gibs (see Fig. 5-16). These are attached either to the uprights or to the press frame, in which location they can easily absorb the thrust force issued by the eccentricity of the drive. Unfortunately, gibs are also subjected to the load forces generated by the tooling, for which reason they are often in need of repair and must be replaced quite frequently.

A plunger-guided slide design in combination with gibbing (Fig. 5-17) absorbs the influence of thrust forces produced by the eccentric drive, with gibs negating the forces generated by the tooling only. Full-length gibs are required for such an application.

5-2-3-1 Link Motion. Another danger to the mechanical press ran by a flywheel energy, which is operating on the basis of a fixed speed and force, emerges after the punches have gone through the pierced material, which happens at the penetration of approximately 25 to 30 percent of the stock thickness. Once without obstruction and nearly at the bottom of the stroke, the ram shoots down at a high velocity. Such an increase in its speed may cause severe shock to both the press and the tooling mounted in it.

To offset this undesirable influence, a link-motion drive was created, capable of controlling the crankshaft's output at that particular moment by reducing the slide's velocity to approximately 40 percent of its original value near the bottom of the stroke. Yet, even with the velocity so reduced, the tonnage, the torque, and flywheel energy remain the same. Such adjustment results in a lesser impact between the upper and lower dies, with reduced repercussions in the press bearings, and other components. Some operations, such as coining and forming, actually benefit from such a slowdown, as the slide velocity remains reduced until after the bottom of the stroke allowing for an extended forming influence on the fabricated material.

A variation of link motion is a draw link, which is used for slowing down the ram in deep-drawing process. And again, the decrease in the ram's velocity allows for a better distribution of material during drawing, which results in lessened tearing, wrinkling, and other defects related to the drawing process.

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5-2-4 Press Drive

The power, which is used to drive mechanical presses, is transformed to the ram with the aid of either:

- Flywheel
- Flywheel and single-reduction gear
- Flywheel and multireduction gear arrangement

In all three types, the flywheel is the storage of energy, being incessantly run by a motor. During the press stroke, it temporarily slows down because of the transfer of a portion of its energy to the ram. Driven by the motor, the flywheel gains speed again in time for another stroke of the press.

Flywheel-only drive is most often used with small dies or where only light blanking is performed.

5-2-5 Crankshaft

To actuate the slide, crankshafts serve as a link between the press drive and the ram. In their basis, crankshafts can be of the following types:

- Crank type (crankpin)
- Eccentric
- Cam
- Knuckle joint
- Toggle mechanism
- Drag link

Contrary to all other types of crankshafts, knuckle joints can generate a tremendous force at the bottom of the stroke. For that reason they are used for compressing operations, which require short strokes at high pressures.

Toggles are actually levers, linked together. Their function may resemble that of a knuckle-joint arrangement, but on close observation, toggles display a faster motion, with longer dwell intervals.

Because drag link mechanisms are slow in motion, they are utilized mostly for drawing operations.

5-2-6 Clutch And Brake

The clutch, positioned between the flywheel and the press drive mechanism, controls the timing of the press by engaging and disengaging the drive shaft to the perpetually rotating flywheel. Clutches can be grouped into three main groups:

- Friction clutches
- Interlocking clutches (positive)
- Eddy-current clutches, operating through the influence of two magnetic fields

Brakes should stop the slide when the clutch is disengaged. Owing to the enormous mass of the whole machinery, the inertia of all its components can be of tremendous proportions, which calls for a good and dependable braking arrangement.

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5-3 PRESS OPERATING PARAMETERS

The energy of the press can be calculated by multiplying its average force by the distance through which it must be applied. The value of such energy is measured in inch-tons.

The power of the press is the amount of energy which must be exerted during a given time interval. Its unit of measure is the horsepower.

Some consider the secret of a good die-operating practice as depending on an adequate amount of pressure, be it the blankholding pressure or the stripping pressure. The selection and arrangement of springs, along with the selection of the press with adequate tonnage, are important here.

5-3-1 Tonnage

The value of press tonnage, as given by various press manufacturers, is based on a certain operating speed of the flywheel. Any difference from the flywheels rpm's will alter the energy output of the press.

In a mechanical press, or other stroke-controlled machinery, the tonnage output will also vary with the position of the ram. When at its lowest, a drop in the press tonnage will be experienced. When the punching force is needed exactly at the moment the ram is at its lowest location, and the amount of stroke is comparatively short, the actual press force can be calculated as follows:

(5-1)

where P_{act} is the actual tonnage, at the bottom of the stroke and C_{dia} is the diameter of crankshaft.

This calculation and the information included in Table 5-1 is not applicable to end-wheel presses equipped with an overhanging crankpin. The preferred range of application is intended for a forged crankshaft, made of 0.45 percent carbon steel with higher elastic limits.

5-3-2 Shut Height

Shut height of a press is the space reserved for the accommodation of the die. It is measured off the top of the bed to the bottom of the slide, with the stroke down and adjustment up.

5-3-3 Stroke

Stroke of the press is the dimensional variation of the slide's movement during the work cycle. The stroke must always be greater than the dimensional distance a die has to travel to operate properly.

5-3-4 Rigidity of Press Construction

One of the main reasons for building the presses as heavy and bulky machines as they are, is the need for consistent accuracy at all times, independent of the press force variation, or

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TABLE 5-1 Approximate Tonnage of Crankshaft Capacity at the Bottom of the Stroke

	Tons	
Crankshaft dia, in.	Single-crank press	Double-crank press
1.375	6	
1.5	7	
1.625	9	
1.75	10	
1.875	12	
2.0	14	
2.25	18	
2.5	22	22
2.75	26	26
3.0	31	31
3.5	43	43
4.0	56	56
4.5	71	71
5.0	88	88
5.5	106	106
6.0	126	126
6.5	150	150
7.0	180	180
7.5	215	215
8.0	255	255
9.0	345	345
10.0	440	450
11.0	545	650
12.0	665	900
13.0	790	1150
14.0	920	1400
15.0	1060	1700

of slightly off center force distribution. The alignment of all press components is very precise, and an unplanned and unexpected overload to a single part may render the rest of the machine out of alignment. The main aspect influencing the whole assembly's working collaboration is deflection.

Where a single component will deflect more than the other complementing parts, a discrepancy in fit and subsequently in function will result. Some press components are more prone to deflection than the others. For example, the shaft, linkage, and ram adjustment–these all suffer more from deflection than–for example, the press frame. Therefore, it may be observed that the proneness to deflection is greater in parts with smaller cross-sectional area, especially where these are being exposed to greater forces.

The rigidity/firmness of press frames could be evaluated as follows:

$$RF = 4.5(RP) \text{ in C-frame presses} \tag{5-2}$$

$$RF = 15.0(RP) \text{ in O-frame presses} \tag{5-3}$$

where RF is the rigidity of the frame and RP is the rigidity of press components.

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Another harmful effect on the press comes in the form of loss of parallelism between the die-mounting surface of the ram and that of the press bed. This deviation from parallel is called *angular deviation*, or *angular distortion*, and it is usually expressed in differences in parallelism between the two surfaces. To properly evaluate this condition, the deviation must be measured not only in an environment free from press force, but in situations where a centrally located force is applied to the tested surfaces, as well as an off-center located force, as shown in Table 5-2.

Another variable affecting the firmness/rigidity of the press, which has a standing effect on the angular deviation of its mounting surfaces is the material from which all force-affected parts are made. Generally, it can be stated that the greater the modulus of elasticity of given materials, the greater deflection and issuing angular deviation can be expected. A less rigid press, made from more elastic materials, will be subject to greater deflection, up to the point where a considerable portion of its output energy will be wasted on the deformation work of its elements. The angular deflection further dictates the working tolerances in press components' assemblies. The press tolerance ranges must always be greater than any dislocation that may result from the lack of parallelism between the press bed and the ram.

There will always be some amount of detrimental influences already present in the function of a press that will affect the angular deformation. There may be nonsymmetrical parts produced in the press, or a progressive diework with less-than-perfect centering of the utilized work force. Other times, the progressive die will be perfectly centered, but not all of its stations will engage in the predetermined operation at the same time, which, in itself, will surely shift the center of the utilized press force elsewhere.

Already the differences in material thickness or material hardness may produce a shift off the central axis of the work force even in perfectly symmetrical parts. Another reason for work force shift are differences in wear of die segments, which are always followed by variation in friction, in force usage and its distribution.

TABLE 5-2 Acceptable Angular Deviation Between the Ram and the Press Bed

	Type of angular deviation	C-press frame	O-press frame
Inches			
No press force applied	Side-to-side	0.00015 in./linear inch	0.00015 in./linear inch
	Front-to-back	0.0003 in./linear inch	0.00015 in./linear inch
Centrally applied force	Side-to-side	0.0004 in./linear inch	0.00025 in./linear inch
along the press axis	Front-to-back	0.002 in./linear inch	0.00025 in./linear inch
Off-center force applied*	Side-to-side	0.002 in./linear inch	0.0005 in./linear inch
	Front-to-back	0.001 in./linear inch	0.0005 in./linear inch
Millimeters			
No press force applied	Side-to-side	0.0045 mm/linear 30 mm	0.0045 mm/linear 30 mm
	Front-to-back	0.0090 mm/linear 30 mm	0.0045 mm/linear 30 mm
Centrally applied force	Side-to-side	0.0120 mm/linear 30 mm	0.0075 mm/linear 30 mm
along the press axis	Front-to-back	0.060 mm/linear 30 mm	0.0075 mm/linear 30 mm
Off-center force applied*	Side-to-side	0.060 mm/linear 30 mm	0.0150 mm/linear 30 mm
	Front-to-back	0.030 mm/linear 30 mm	0.0150 mm/linear 30 mm

* The off-center force should be located in $^1/_4$ of the width of the press (left-to-right), and in $^1/_4$ of the depth (front-to-back). The force should be equal to $^1/_4$ of the max. press force.

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5-3-5 Press Controls

There are quite a few diverse elements involved in the press control. Previously, a single motor equipped with a starter and a disconnect switch was all that was used. Today, the complexity and intricacy of press control systems and its components is dependent on pneumatic, hydraulic, electronics, electrical, and electro-mechanical enhancements. Where before the operator simply pressed a "Start" button and terminated the press operation by pressing a "Stop", a wide range of commands, with sequences of predetermined loops of operation, supported by an array of limit switches, sensors, relays, air or hydraulic cylinders, motors, and other components are used (see Fig. 5-18 for the size and complexity of the control panel).

Programmable logic controllers (PLCs) can nowadays be programmed to respond to every need of the press operator, or even guide the press in an automatic production environment. The automatic function of a press can be adjusted to any scenario such a machine can encounter. Should a valve need be opened to provide for a shift within a press mechanism, the PLC can be programmed accordingly and the desired shift will occur precisely, on time, with dependence on the parameters given.

FIGURE 5-18 Verson 1000 ton Link Drive Blanking Press, model LE4-1000-180-96T and integrated blanking line control console. Link drive provides fast advance and slow down during the blanking portion of the stroke to increase production while reducing the shock associated with the blanking operation. This press is typical of automotive blanking presses with 12 in. stroke and speed ranging from 20–60 SPM. (*Reprinted with permission from Verson and Danly Division of Enprotech Mechanical Services, Inc., Lansing, MI.*)

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Automatic punching machinery, or *numerically-controlled* (NC) presses, sometimes also called "turret presses" are operating on the basis of NC commands, previously contained on a punched paper, or mylar, tape, today transmitted to the machine via computer network. For some strange reason, NC presses are sometimes erroneously called CNC presses. In the U.S. industry, the term "CNC" is reserved to rotating, numerically-controlled machinery, such as milling centers, lathes, and similar. The meaning of both acronyms, *numerically-controlled* (NC) and *computerized numerically controlled* (CNC), is the same, yet the distinction is kept to separate the two groups of machines, punch presses as NCs and rotating machines as CNCs.

5-4 PRESSES, ACCORDING TO THEIR OPERATION

After classifying presses according to various aspects of their construction and use, differentiating them according to the type of their operation is the final point of distinction of this type of equipment.

5-4-1 Single-Action Press

Single-action presses are used for general press work throughout the industry. The number of "actions" is given by the number of slides, or rams, operating on a common axis and mounted within the same frame.

5-4-2 Double-Action Press

A double-action press (Fig. 5-19), as its name implies, has two slides operating along the same axis yet independent in their movements. Where the first slide may be actuated by the usual means, the other slide has a different operating arrangement. Quite often, a cam-dependent movement tied to the first slide's function is utilized.

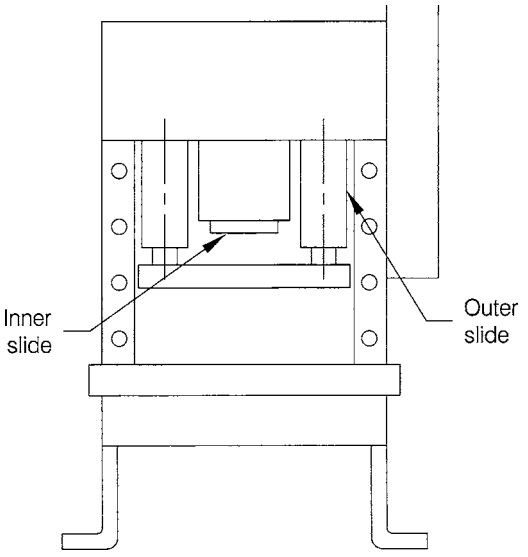

FIGURE 5-19 Double-action press.

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In double-action presses, the second slide, being an additional mechanism, is spaced around the first, original slide.

A double-action drawing combination has the drawing punch attached to the inner slide and the blankholder mounted to the second, outer slide. The whole operation can be adjusted to conform to a sequence, where the blankholder will come down first, retaining the part to be drawn, and only then the main slide with the drawing punch will follow. On coming up, the drawing punch leaves first, while the blankholder is still in its place, to retain the drawn part and prevent it from following up with the tool.

5-4-3 Triple-Action Press

A tripe-action press has three slides, independent in their movement yet assembled within the same press frame. These presses are quite useful for complex drawing operations, where—for example—drawing has to be performed in more than one direction. In such a case, the first drawing punch and the blankholder may draw the part to the appropriate size and dwell to allow for the third slide's movement, which pulls the material in another direction.

5-4-4 Multislide Press

Multislide presses may contain several slides assembled within a single press frame, with their range of operation along various axes. These slides may perform all kinds of work, either progressive or not. Such an arrangement is actually the same as if several presses were taken out of their shells and squeezed into a single machine frame.

5-4-5 Hydraulic Press

Hydraulic presses are slower than mechanical presses, but their tonnage force is maintained constant throughout the stroke, no matter at which position the ram is located. Their total tonnage may be lowered for fragile die equipment. Double-action hydraulics can have the tonnage adjusted for both sections, for the punch holder and the blankholder as well.

Hydraulics cannot be overloaded, as they are protected by a combination of two separately adjustable relief valves. Die setup is easier, since they do not need to be adjusted for variation in material thickness. However, their motors must be larger than those of mechanical presses because they have no flywheel to store the energy.

Blanking operations can be detrimental to the hydraulic system, as the shock of puncturing the metal endangers its components. Their main range of application is for drawing, where hydraulics are an excellent choice, mainly because they maintain a constant pressure on the drawn part, progressing at more adaptable rates. Mechanicals enter the drawn part full-force and slow down at the bottom of the stroke.

As mentioned previously, repairs of hydraulic presses, even though fewer, are much more complex and demanding, as the source of their breakdowns is hardly ever detectable visually.

Lately, hydraulics are slowly being accepted as replacements for mechanical presses, in which capacity they are often utilized for blanking and piercing operations as well. The output rates of hydraulics improved over the time, with 20 to 40 pieces per minute where producing parts up to 15 in. [380 mm] in size, and up to 60 parts per minute with 1 to 2 in. [25.5 to 51.0 mm] sizes of products.

Usually, the production being diverted to a hydraulic press consists of parts with

- Lower production rates per each run
- Production known for material thickness inconsistencies
- Parts demanding longer power strokes

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- Dies difficult to setup
- Dies in need of variable ram speeds
- Parts with a greater locating accuracy and precise position control

Hydraulics are easier to setup and their changeover time is lower than that of mechanical presses. Where problems with jamming of parts is expected, hydraulics can be of help, for their built-in overload protection prevents damage to the press by rendering it force-limited, where needed.

Another advantage of hydraulics is the constant output force, which is available in equal amounts through any portion of the stroke.

5-4-6 Mechanical-to-Hydraulic Hybrids

It must be admitted that ordinary mechanical presses can nowadays be refurbished to behave similarly to hydraulics. Equipped with a hydraulic cushion and controlled by the proper software, the existing mechanical presses can now be turned into versatile mechanical/hydraulical machines of future pressrooms. This innovative approach, having no competition worldwide, was developed by Red Stag Automation Inc., WI, who took a pioneering step ahead by experimenting with cold-forming applications under the restricting aspects of controlled sensitivity to the pressure and forming characteristics of the material.

Their hydraulic cushion allows for adjustment of the pressure profile by altering the press tonnage at any given segment of the stroke, in tune with requirements for the actual location of force application. The resistive force of the hydraulic cushion acts against the press in such a way that by offering a selective resistance, the press tonnage is being manipulated with respect for the part being produced. The restrictive force of the cushion can be preselected to be any range between the maximum tonnage of the press all the way to that of zero.

The cushion consists of three tables, each of them equipped with a powerful hydraulic cylinder at each corner (see Figs. 5-20 and 5-21). The tables can be operated separately, or as a group. There is an eight-point gibbing arrangement for every table.

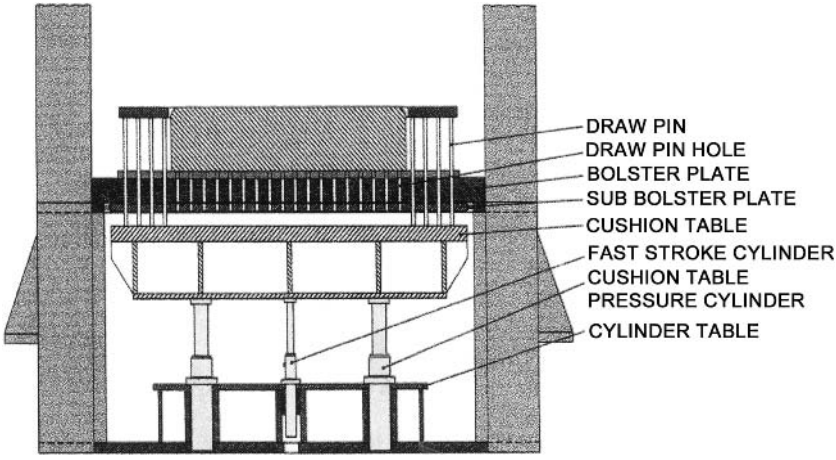

FIGURE 5-20 Diagram showing the location of components of a hydraulic die cushion. (*Reprinted with permission from Red Stag Engineering & Automation, Inc., Waupaca, WI 54981.*)

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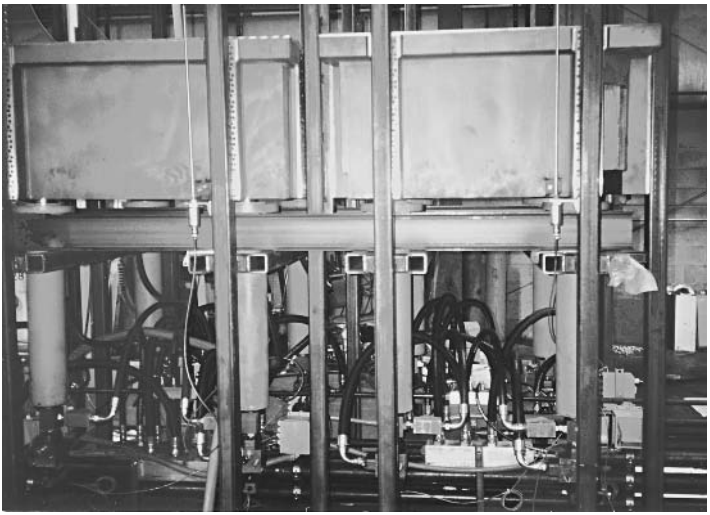

FIGURE 5-21 Hydraulic cushion for a press bed, consisting of three separate tables which are either independently or simultaneously operated by hydraulic cylinders, as guided by the company's *Infinite Control* computer software. (*Reprinted with permission from Red Stag Engineering & Automation, Inc., Waupaca, WI 54981.*)

Their *Infinite Control* software, originally developed for cold-forming applications, assists with determination of the force selection needed for a particular product and for a particular material. Sensing and reporting to the PLC the material resistance encountered at areas of problem, the software manipulates the press and hydraulic cushions tonnage along with their timing, thus capable of overcoming the obstacles of material distortion, defects, or tearing. Suddenly, the material properties, its gauge and grain direction, its composition structure, are becoming immaterial and perfect parts are produced with each stroke of the press.

5-5 OTHER PRESS-ROOM MACHINERY

There is a host of other press-room machinery needed to supplement the function of presses. Out of the whole array of equipment, several samples were selected for illustration (see Figs. 5-23 through 5-25).

There are coil straighteners, coil feeds, coil unwinding and coil rewinding equipment, destacking systems, automated sheet feeders, feeding lines, transporters, robots, tooling and automation devices, scrap cutters, and others.

As with every manufacturing operation, even feeding of the coil stack or that of blanks has its areas to watch out for. For example, where a surface finish is not congruent with the method of feeding, accurate positioning of the material may be jeopardized. Where slippery surface of the strip can slide off the gripping or feeding devices, discrepancies of all kinds may emerge. So-called galvanized materials (i.e., dip coated), or surfaces treated to a lubricant can definitely pose a problem in strip feeding. For these reasons, the

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fabricated material would better be lubricated only after it passes through the feeding device.

Same with prepainted strips or sheets, or with surfaces to which some cosmetic requirements are tied: these can be scratched in the process, marred by stops of the feeding rolls in the straightener, or damaged when passing through the feeding equipment.

A care must be exercised when straightening or feeding other sensitive materials, such as stainless steel, high-carbon steel, and some alloys. Here the problem is with the equipment's rating, which is always geared to processing a mild steel. Where tougher materials are to be fed or straightened, their yield strength and the shear strength may render the existing shop equipment useless. Therefore, a careful evaluation of the equipment and its usage with respect to materials it has to handle must be exercised prior to committing to a production of a specific product.

5-5-1 Coil Straightening Equipment

The coil as manufactured in the steel mill and slit to the proper width is either ribbon-wound around the core or oscillated-wound. A *ribbon-wound coil* is that, which is wound on top of itself, over the previously-placed coil surface. Such coils are but a coil-width wide and where this dimension is below 1 in. [25.4 mm] they may fall apart in handling.

Oscillated-wound coils are placed next to each other, similarly to the thread wound on a spool. Such coils are wider, as they can accommodate several widths of the slit strip material. Once installed in the coil feeding equipment, oscillated coils last much longer without changing, as for the same diametral size, oscillated coil may contain equal of 20 to 25 ribbon-wound coils.

Almost every coil that comes to the fabricating plant includes a so-called coil-set, which is a condition caused by the coil's wounding process. This is a curvature in coil, which can make it very difficult to load the beginning of the strip into the press. Therefore, as a step in-between, coil straighteners are being added to the coil feeding lines (see schematics in Fig. 5-22 and photo in Fig. 5-23).

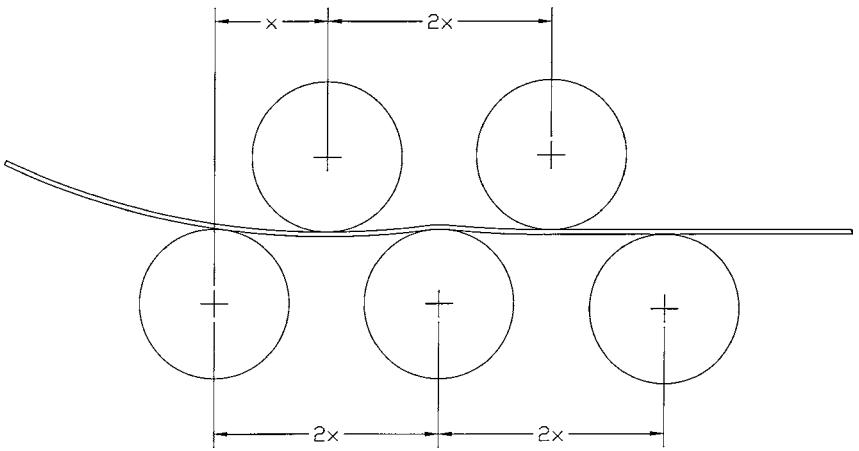

FIGURE 5-22 Coil straightening with rollers.

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FIGURE 5-23 Straightener with eddy-current drive. (*Reprinted with permission from Minster Machine Co., Ohio.*)

Straightening of coils is done by rollers, which are staggered so that a strip material is being formed either way until it comes out straight, as shown in Fig. 5-22. Here the distance between the rollers plays an important role, as they must be spaced in such a fashion, as to support only the elastic deformation of the straightened material.

Usually, five or seven rollers are being used by stamping facilities for coil straightening purposes. The number of rollers needed to straighten any given material is dictated by the amount of set the material contains. The diameter of rollers depends on the thickness of the straightened material with a rule of thumb being the greater the material thickness—the larger the roller diameter should be.

5-5-2 Coil Feeding Equipment

The two main groups of coil feeding equipment consists of roll feeds and gripper feeds. Their subgroupings can be assigned with dependence on the source of their power, be it the press itself, or be it driven by a shop air system, hydraulically, or by a servo-motor drives.

5-5-2-1 Press-Driven Feeds. The press-driven feeds can be cam feeds, or rack and pinion variations of the same. Of advantage is that their speed of feeding is always synchronized

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with the function of the press and should the press stop, the feeding of material will stop too. This synchronization makes such types of feeding arrangements desirable in high-speed environment, or where unloaders or destackers are being used (Fig. 5-24).

Of disadvantage is their lack of timing adjustment, which does not allow for any advanced feeding of material to the press until the deepest drawing die in a sequence of tooling operations, disengages.

Being inherently tied to the press operation, press-driven feeds cannot be persuaded to jog the strip for threading, unless electrical controls are implemented in their function. But their gradual acceleration and deceleration of speed, accompanied by no sudden stops or jumps of the fed material, allows for high-speed indexing with acceptable accuracy.

5-5-2-2 Gripper Feeds. Gripper feeds use a linear motion combined with a pair of clamps (grippers) for strip advancement, which is limited to a certain given amount only. In gripper feeds' function, which depends on a shop air or hydraulic-powered cylinders for movement and for engaging the material, the feed gripper is used to clamp the material to be moved. This gripper extends and at the same time, the material-retaining gripper retracts, releasing the material for movement. The feed pulls the material along using the feed gripper.

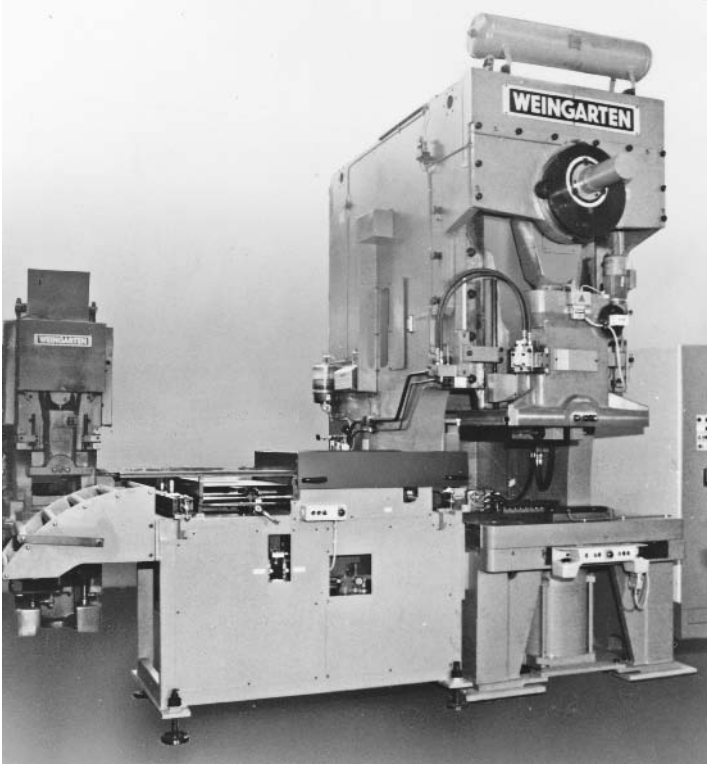

FIGURE 5-24 Tongs feed unit, combined with a press. (*Reprinted with permission from Müller Weingarten AG, Germany.*)

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The disadvantage of this type of feeding is the reliance on the shop air, which provides slower feeding speeds, lacks accuracy in positioning of the strip, and needs much more maintenance than other types of feeding mechanisms. Additionally, the initial setup is more time consuming and the advantage of the system's lower cost can be quickly negated by new electronic roll feeds, which are using smaller servo feeds for material movement.

5-5-2-3 Roll Feeds. Electronically driven (servo) roll feeds are far more superior in accuracy of feeding, while being quicker and requiring less maintenance (see Fig. 5-25). The range of material widths is greater, which, combined with the possibility of preprogrammed paths, allows for previous setups to be recalled and used at a push of a button.

Roll feeds allow for jogging of the fed material, for feeding in both directions, for fine-tuning of feeding operation prior to production run. They can run a wide variety and combinations of material widths, material thicknesses, and lengths of feeding. There is lowered need for maintenance of this equipment and their life is longer than that of air- or hydraulic-feeds.

5-5-3 Other Press-Feeding Arrangements

Among other press-feeding equipment are mainly automated blank destacking systems, automated feeding devices, robots, and similar. All these automatons may loosely fit into

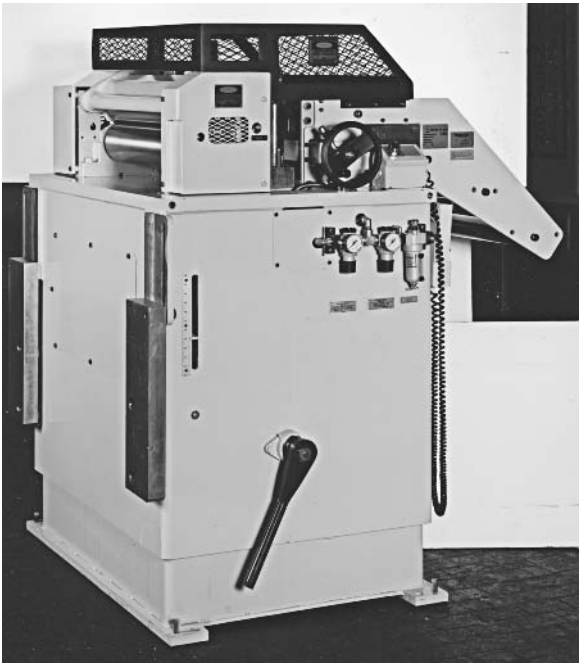

FIGURE 5-25 Electric feed, servo-driven. Adjustable feed length during operation. Adjustable feed angle (dwell & position). No set-up required for material thickness. (*Reprinted with permission from Minster Machine Co., Ohio.*)

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the same category of products, with adjustments for their span of feeding movements, flexibility of their own positioning, and adaptability to different types of machines.

Automated devices must often be selected with a particular operation in mind and their reprogramming and readjustment must be borne in mind when switching to other operations. Therefore, longer production runs are favorable when opting for automated feeding, or for such devices that allow for a quick change, or a recall of previously programmed task sequence.

Automated destacking systems feed single blanks into the machine, after attaining their separation beforehand, with magnets. The actual transfer is done via suction cups with magnetic rollers or magnetic belt conveyors. As previously stated, the condition of material's surface is important here, as the grippers may often be affected by oily or slippery surface of the part, in which case feeding of the machine may become a problem. Yet, destackers themselves are capable of washing the blanks, or of lubricating their upper or bottom surface. It may be that a proper combination of destacker and lubricant is of greater importance here than the absence/presence of the lubricant or painted surface.

Destacking and blank loading units can handle 1000 to 1500 large parts per hour. They operate alone, even at night, they do not need the lights, heat, nor any other comforts of the modern press room. Where the stock to be fed into the press must be replaced by another material, the programming of the unit may be adapted to do just that. In such a case, the stack-retaining arrangements are shifted around, magnets are instructed to assume different positions, the length of the stroke changes, and a new production can begin almost without interruption.

Of essence is the proper positioning of the blanks to be fed. Pallets with nests must be utilized, where blanks are restricted from movements by positive stops. Often, pin-nested pallets are designed and used with success. Feeding of blanks is protected by a double-blank detector, which identifies a misfed part and reject it into a prespecified location.

5-5-4 Scrap Cutters

Scrap cutters are not always considered in the basic die design and this omission may create numerous problems later on, in production. Suddenly, to everyone's surprise, there may be long, unmanageable strips of flimsy, laced scrap material pouring out of the die, impossible to deal with. Chopping them off at random may send small pieces of scrap flying all over the press bed, if not over the die, with nobody wiser on how to remove them.

Scrap cutters are important devices, which have to be allocated for every die and thoroughly evaluated for suitability and compatibility with that manufacturing process. Their location and function should be planned with other automated equipment in mind, be it the strip feeding devices, or crane's movement for delivery of additional coils, or lift truck's access for removal of finished parts.

Scrap cutters can chop the remaining strip into small pieces, which will easily fit a scrap bin and be disposed of. Where a scrap cutter cannot be added as a component of the die because of additional press force needed for its operation, stand-alone scrap cutters should be utilized.

Often, just better planning of the die layout can take care of scrap cutting. The material to be removed and disposed off can be pushed toward the die edge by the advancing strip, from where it may fall down by itself, thanks to gravity. Of course, proper guidance along the path of its fall should be provided and supported by channels or chutes, positioned under angles of proper steepness, so that the scrap is not obstructed in any way and falls down exactly where expected. Usually, a 60° angle from the horizontal was found suitable for most scrap removing situations.

The best way to dispose of scrap is to let it fall down the shortest path possible. Where this is not possible, simple chutes should be built to guide the scrapped material to its destination. One thing should be always remembered that all the scrap must be removed from the die block (or from the press bed) each time the press comes down. Leaving the scrap

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hanging around may prove dangerous to the operator, dangerous to the work, and dangerous to the equipment.

5-6 PRESS MOUNTING, PERFORMANCE, AND PRODUCTIVITY

There are several factors affecting the productivity of a press. The first of all, and perhaps the most important, is the proper rigidity and sturdiness of the press bed and frame. This depends mainly on the proper mounting of the press, on its foundation and leveling. Press feet should be positioned on felt pads or heavy-duty rubber supports. The concrete floor underneath must be free from irregularities, be flat and leveled. With poorly leveled concrete slab, some tend to repair the differences with steel shims, yet these may slide during press operation and endanger the machine and its surroundings.

Where irregularities in the press foundation may be encountered, leveling with grout may be used to provide for the differences. The best test of the surface condition, of course, is the press itself, which, when positioned on its planned footprint, will show discrepancies where they are. Leveling of these may be achieved with the press already in place, by temporarily jacking it up and shimming, for the time interval the grout or any other recommended press-mounting material takes to cure. The proper positioning may then be secured by bolting each foot of the press into the foundation.

With mounting of small gap-frame inclinable presses and gap frame stationary presses, we often may get away with just leaving them on the rubber or felt pads with no specific foundation requirements. Large presses are sensitive to alignment and sliding from their assigned position over an uneven foundation may misalign their elements, along with the finely-aligned elements of the die mounted there, and damage may result.

Presses with heavy-weight slides (i.e., rams), especially high-speed presses, require a careful study and a thorough analysis before selecting the proper mounting and foundation requirements. Often, the press manufacturer specifies a 1.5 times the dead weight of the press along with the heaviest die it may accommodate, to be taken as the actual weight factor in foundation design. This way overspecifying of parameters and overemphasizing on sturdiness and flatness/leveling requirements may, in this case, prove beneficial.

In some cases, using high-dampening-level press-mounting isolators may help and it is often a preferred way of press mounting to that of bolting the press directly to the floor.

Pertaining further to press sturdiness, its construction should include full-length tie-rods, to keep all main members, such as the bed, the crown, and the uprights, properly connected. A thicker bed and bulkier uprights are always preferable on a press, as these protect them from deflection during the press function.

Additional factor affecting the productivity of a press, its performance, and its life, are mainly related to the maintenance and repairs of the equipment.

5-6-1 Press Maintenance

Where a preventive maintenance is scheduled and performed, where the repairs are not postponed (often *ad infinitum*), such presses function better, have less alignment problems, and their overall life span is extended. But where these machines are neglected, disasters may sometimes occur.

Some preventive maintenance-related issues are the inspection of all bearings' clearances, gib's clearances, measurements of the ram's parallelism, inspection of the perpendicularity between the ram's movement and the bed surface, and the check of the brake's lining. However, additional areas should not be overlooked when inspecting the press.

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These are for example the condition of lubricating system, the condition and cleanliness of filters, evaluation of the oil type used for its compatibility with press manufacturer's recommendation, and similar items. A press manufacturer's maintenance requirements should be taken as a standard and followed to a dot.

5-6-2 Press Overloading

Quite often, a press can be overloaded where it does not even seem possible. Already the fact that a sudden break through the material in piercing or blanking operations may send the ram speeding down, is worth mentioning again.

Where the press is overloaded above the bottom dead center, a torque overload may result. In this scenario, the excess force travels up through the crankshaft into the gears, where it may shear keys, chip or break off gear teeth, and twist-break clutch shafts. Its influence on the crankshaft is that of a twisting force, for which reason such overload is called a *torque overload*.

Tonnage overload happens when the press is subjected to the overload at the bottom of the stroke. The excessive force produces cracks in crankshaft mains and other connections, cracks in threads of screws and nuts, cracks in ram pockets, in press bed, in knuckles, and in the crown. Such cracks are very difficult to discover and only after the press had been taken apart, its components cleaned, can the cracks be, sometimes, visible.

5-6-3 Die Positioning

Presses are bulky, heavy, and sturdy machines, but they are extremely alignment-sensitive. Incorrect mounting of the die may only cause additional damage. For example, mounting of a die off center (left-to-right) will place a heavy pressure on the gibs and the ram, and on all connecting elements. Mounting the die off center (back to front) may leave a portion of the ram unsupported causing the development of cracks in its wear surfaces.

A small die mounted in a large-bed press generates a bow in the ram and a bow in the bed as well, right in the middle, which, if repeated long enough, will certainly give rise to cracks in these areas. Majority of presses are designed to have approximately two-thirds of their bed area covered up with dies. Where this is not observed, additional problems may develop.

The same way the overall function of the press should be constantly controlled and serutinized, as the proper functionality and reliability of its components is of vital importance. After all, the whole machine is but an assembly of its components.

5-7 ELECTROEROSIVE MACHINING

Electroerosive machining is a newer machining method utilizing a bombardment of the metal material with the influence of electric current, accompanied by an appropriate cooling liquid. It is a process of metal removal, which can be used for production of cuts of various shapes, unattainable otherwise.

Electroerosive machining can be divided into two basic groups:

- *Electrical-discharge machining* (EDM), sometimes also called electrodestructive machining, which consists of cutting, pocket cutting, and grinding processes. The electrode is a metal wire or a thin metal strip, surrounded by the dielectric liquid. In the grinding application of this process, the electrode rotates around its own axis.

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- *Electrochemical machining* (ECM) is used for production of pockets in the metal material, or for grinding, polishing, and similar finishing operations. The process uses a rotating electrode, and the coolant is of an erosive nature, the action of which speeds up the removal of material while slowing down the wear of electrode. However, the accuracy of this method is less than that of EDM.

Because of the widespread utilization of EDM machining, only the first manufacturing method is treated in greater detail here.

EDM machining, or electrical-discharge machining, is used for production of a wide variety of cuts and shapes. In this process, a wire electrode is inserted through the metal workpiece, where by discharging electricity, it forms a localized arc between itself and the metal material. The electrode is made of either brass, copper, or tungsten. Where solid-block electrodes are used, these are usually made of copper or graphite. They wear quickly, for which reason they are often stepped in shape for cutting. A three-stage EDM electrode is shown in Fig. 5-26.

The EDM process is quite similar to a short circuit caused by touching the source of energy with a metal screwdriver. The electric spark so created erodes the metal surface in the point of contact. Because of the extremely high temperatures of the EDM arc, the eroded metal material literally melts away and evaporates, leaving a slight gap (Fig. 5-27). The dissolved metal is washed away by a coolant, which is usually a deionized water, petroleum, or oil. The scrap takes the shape of little balls of compact metal dust. These sometimes get deposited back on the work surface, adhering to it as if welded.

The temperature between the electrode and the workpiece is enormous, with the arc being produced at high frequencies of many thousandths up to many ten-thousandths times per second. The dielectric coolant does not affect the spark, its influence being confined to the dissolved metal.

In this type of machining process, some overcut is always present. The depth into which the spark affects the metal may often be 0.004 in. (0.1 mm) per side, which adds up to 0.008 in. (0.20 mm) per diameter. This is the amount of additional and undesirable metal removal should the electrode's size be the same as the opening (see Fig. 5-27).

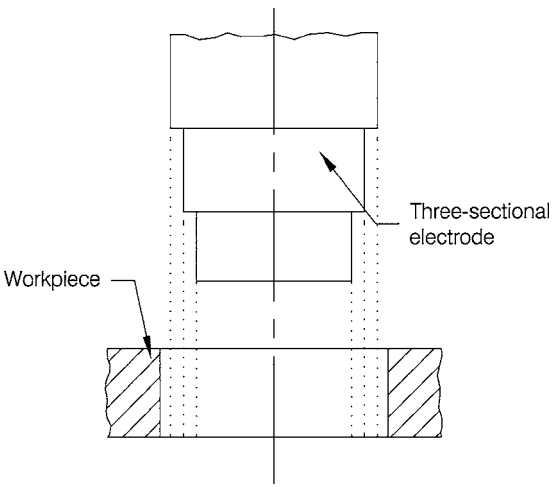

FIGURE 5-26 Three-stage EDM electrode.

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METALWORKING MACHINERY

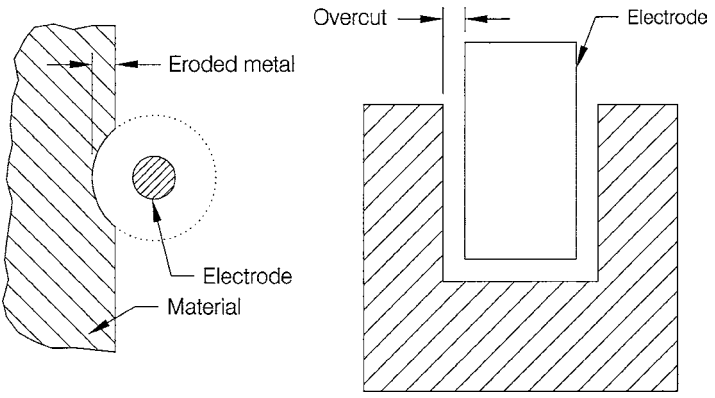

FIGURE 5-27 EDM work process.

The surface condition of EDM cuts and the amount of overcut depend on the operating frequency and on the electric current going through the EDM equipment. With the increase in frequency, the surface condition improves and the amount of overcut diminishes. With the increase in current, the overcut increases and the surface condition becomes worse.

Usually, the EDM cut is achieved in two phases: first a rough cut, followed by a finishing cut. An allowance for the second cut must be made in the size of the first opening. The finish obtained with the second cut is finer, even though the cutting process itself is faster. This is due to the much smaller amount of material being removed the second time.

EDM-produced cuts are not always straight because of the inclination of the electrode's surface, eroded by wear (Fig. 5-28). The arc, aside from removing the metal material from the workpiece as it should, also removes portions of the electrode in places of contact.

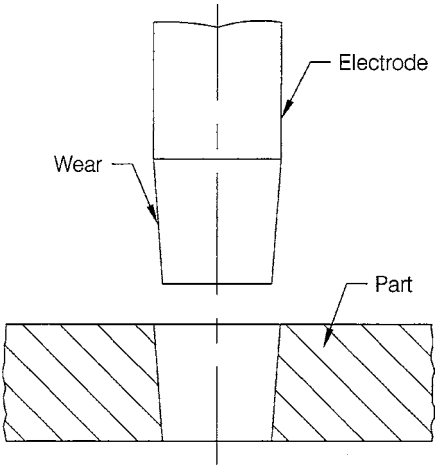

FIGURE 5-28 Angular wear of the electrode.

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There are many advantages to the EDM process: Complicated shapes can be produced in a fraction of the time it used to take. Complex-shaped dies can be made in one piece instead of being sectioned to ease their machining. Metal blocks can be hardened prior to EDM cutting. Punch and die may often be made with the same cut, provided the amount of obtained tolerance (overcut) is acceptable.

A definite improvement of machining methods can be achieved with EDM undercutting capacities, as shown in Fig. 5-29. With a variable movement of a single electrode, multishaped undercuts can be attained, including slanted, angular surfaces, where the angle of inclination is either opening or closing toward the bottom of the block.

However, there are also disadvantages, the worst of them being the detrimental effect the EDM process has on the surface condition of the material. An underlying root of this problem is the continuous process of melting and solidification of the surficial layer of material. The effect of the extensive heat produced by the arc melts the material in its immediate vicinity, which is followed by its immediate cooling. This sequence is constantly repeated at great speed, and its effect on the surface of the material is enormous. First of all, a considerable brittleness of the upper layer develops, accompanied by a tendency to cracking. The depth of these cracks depends on the working temperature of the electrode: With higher temperatures, the depth of surficial fractures increases.

Underneath the first layer, the adjacent material is heated as well, but it does not melt, since its temperature does not reach such high levels. However, an alteration of its properties does occur, followed by changes in its structure and overall condition. The fatigue strength is decreased, cracks and microcracks appear, and a general degradation of the material follows.

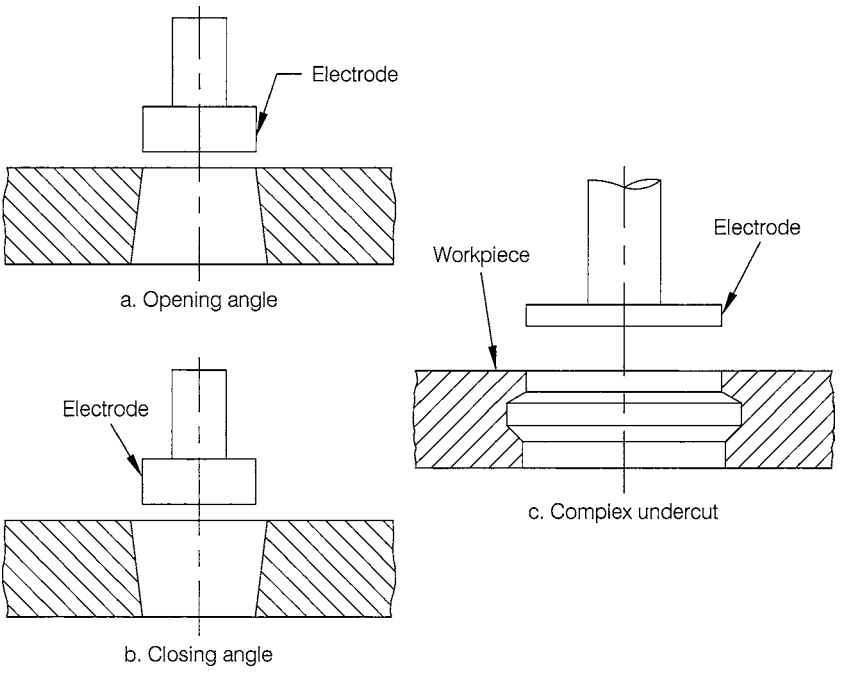

FIGURE 5-29 Electrode cutting and undercutting.

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In maraging steels, the effect of the EDM process on the surface condition is still more pronounced, in some cases almost detrimental to the quality and functionality of products made from these materials. Here, some tensile residual stresses of considerable proportions are introduced into the material, causing the formation of cracks and microcracks. With parts subjected to cyclic loading, such as springs, these imperfections are enhanced quite rapidly, progressing toward a fatigue-dependent premature failure of products.

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CHAPTER 6
BLANKING AND PIERCING OPERATIONS

6-1 METAL-CUTTING PROCESS

Metal cutting is a process used for separating a piece of material of predetermined shape and size from the remaining portion of a strip or sheet of metal. It is one of the most extensively used processes throughout die and sheet-metal work. It consists of several different material-parting operations, such a piercing, perforating, shearing, notching, cutoff, and blanking.

In blanking, the piece is cut off from the sheet, and it becomes a finished part. In piercing, the cutout portion is scrap which gets disposed off while the product part travels on through the remainder of the die. The terminology is different here, though both processes are basically the same and therefore belong to the same category, which is the process of metal cutting (Fig. 6-1).

The actual task of cutting is subject to many concerns. The quality of surface of the cut, condition of the remaining part, straightness of the edge, amount of burr, dimensional stability—all these are quite complex areas of interest, well known to those involved in sheet-metal work.

Most of these concerns are based upon the condition of the tooling and its geometry, material thickness per metal-cutting clearance, material composition, amount of press force, accurate locating under proper tooling, and a host of additional minor criteria. These all may affect the production of thousands and thousands of metal-stamped parts.

With correct clearances between the punch and die, almost perfect edge surface may be obtained. This, however, will drastically change when the clearance amount increases, and a production run of rough-edged parts with excessive burrs will emerge from the die.

Highly ductile materials, or those with greater strength and lower ductility, lesser thicknesses or greater thicknesses—these all were found similarly susceptible to the detrimental effect of greater than necessary clearances.

The literature recommends different tolerance amounts for cutting tools. Some claim $0.06t$ (t = material thickness) to be sufficient for almost all applications. Others promote a $0.08t$ range, with $0.1t$ topping it off.

We already know from Chap. 2 that the shearing process consists of the punch moving toward the die opening, with sheet-metal material in between. The pressure applied to the strip causes the development of various compressive and tensile forces within the material. It begins to crack in the immediate vicinity of the edges of both cutting elements (Fig. 6-2). The progression of cracks finally results in separation of the cut area off the sheet, and the part is blanked (or pierced, perforated, and the like).

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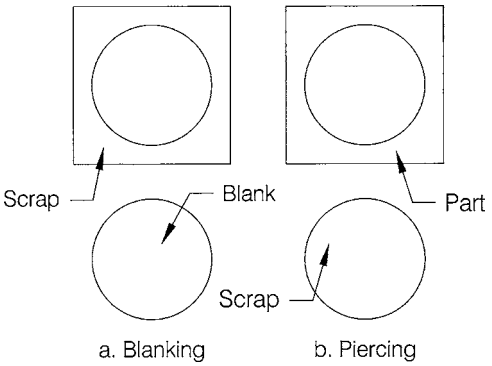

FIGURE 6-1 Blanking and piercing differentiation.

Naturally, a different type of separation must occur with a softer material than with its harder counterpart. The carbon content certainly has an influence on this process as well. Therefore, the tolerance range must have a provision to change not only with the stock thickness but with its composition as well.

As already mentioned, good condition of tooling is absolutely essential to the cutting process. We may have the most proper tolerance range between the punch and die, and yet the cut will suffer from imperfections if worn-out tools are used.

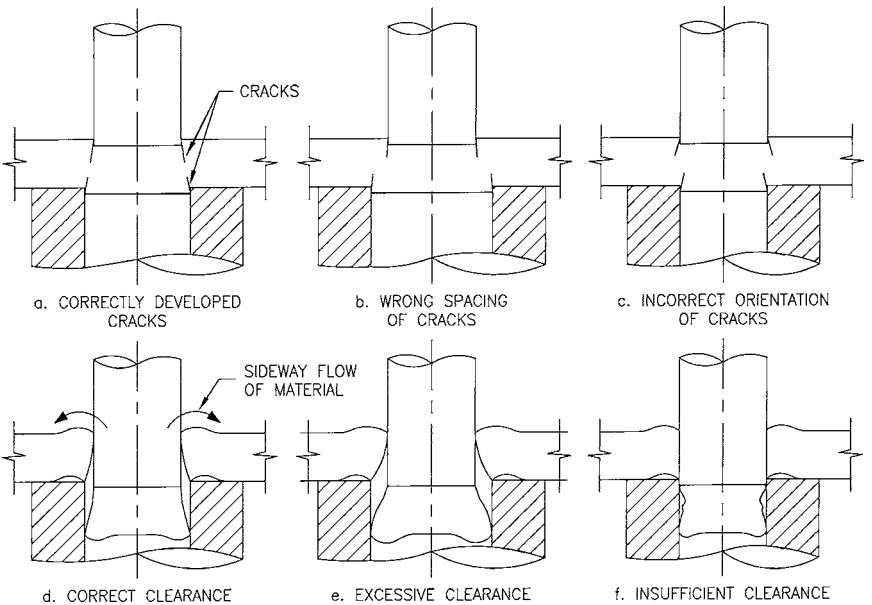

FIGURE 6-2 Shearing of metal.

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BLANKING AND PIERCING OPERATIONS

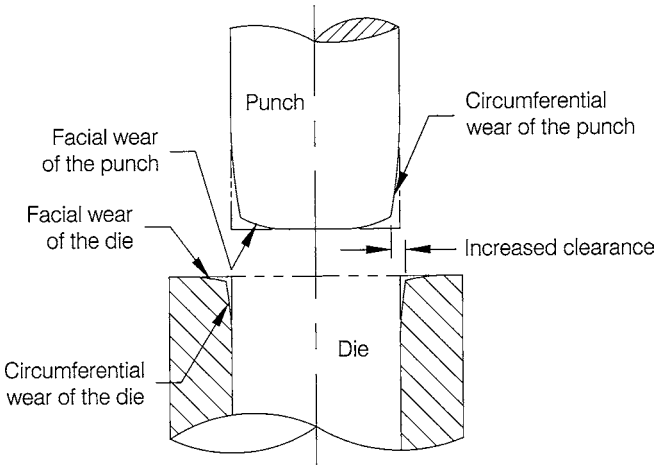

FIGURE 6-3 Wear of tooling.

The wear of tooling (Fig. 6-3) considerably alters the cutting conditions, raising the demand for press force as well. Up to 50 percent increase in tonnage has been observed with some parts. The punch-and-die clearance enlarges, with subsequent damage to the surface of the parts, which becomes rough and uneven. Excessive friction, followed by an increase in temperature during the die operation, only speeds up the destruction process.

6-2 FORCES INVOLVED IN THE METAL-CUTTING PROCESS

Aside from the press force acting upon the ram and applying vertical pressure to the die and subsequently to the steel-metal material, additional forces are involved in the metal-cutting process. As the punch enters the material, it pushes the bulk of it down through the opening in the die. However, a small portion of metal is forced sideways, as seen in Fig. 6-2. This flow, directed away from the cutting tool, is guided by the action of tensile and compressive forces which develops within the cut metal, and is thus grain dependent: A different pattern of flow is seen along the grain than against it.

Such movement of material affects the structure of the sheet, especially in the immediate vicinity of the cutting station. Forced aside, the material becomes too crowded by such expansion in its content and it resorts to bulging through the only available outlet, through the surface of the sheet, which it deforms. In areas where piercing is more congested, the deformation progress is so widespread that the whole sheet becomes distorted, displaying either an excessive camber or waviness or any other variation from straightness.

The expanding material pushes also against the body of a punch, applying a side-oriented or thrust force toward it. The punch is suddenly restricted in its movements by the squeeze of bulging material, which is accompanied by changes in friction, as well as increased heat. The stability of the punch is often threatened and slim and fragile tools can often break under such a load. The deformation of the cutoff portion of metal is often not so pronounced, which is probably due to its usually smaller size.

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The calculation of thrust force on the blocks and calculation of deflection can be found in Chap. 2 (formula 2-16), Chap. 3 (formulas 3-1 and 3-2), and Chap. 4 (formulas 4-4 through 4-9).

From Fig. 6-3 it is obvious that the flow of tensile and compressive forces resulting in the development of side-oriented and expansive shifts within the material is also a great contributor to the emergence of wear of the working surfaces. According to some, a side-oriented force generated by the cut material may amount to 2 to 20 percent of the total blanking force, with its marked dependency on the material thickness, its composition, and the amount of clearance between the cutting surfaces.

Additionally, forces within the cut material further influence the size of a sheared opening. On the complete retrieval of the punch, the bulging material slightly flattens out, its movement being oriented toward the empty space, which subsequently gets reduced in size. Cutting clearances of up to $0.05t$ have been found to produce openings smaller than the size of the cutting punch.

As already mentioned, the punch on its way out of the cut material is restricted in movement by the emergence of frictional forces originating within the structurally altered material. For the punch to progress, a considerable force is needed to overcome this influence. This force, called a *stripping force*, may be calculated with regard to the material composition, its strength and thickness, the size of tooling, and its clearance.

Naturally, with increasing clearance between the punch and die arrangement, the amount of stripping force decreases. But the quality of the cut decreases along with it.

6-3 ALIGNMENT OF CUTTING TOOLS

Punches entering the material must be absolutely concentric with the die opening below. But sometimes a shift from the mutual axis may be due to the assembly procedures; sometimes a minute movement in the frame of a press may cause a slight offset of the two centerlines, which ideally should match each other.

Even with perfect positioning, a long, unsupported, and unguided punch may be swayed aside by the movement of metal during the cutting operation or by its own off-center punching, or by an action of some other demanding operation within the die.

To alleviate this problem, punches should be guided in their movement unless their bulk is so great that they actually constitute the major portion of the die.

The guidance can be provided through inserts in the stripper plate, which are appropriately called *guide bushings*. Slim punches should be further protected by punch sleeves, or wraps, and similar arrangements. Punches that have irregular shapes or those having their face area ground to an angle often utilize heels, which guide their progress during the cutting operation (Fig. 6-4).

Multipart retainers are an additional punch-guiding provision to a die. They resemble small, self-contained punch plates, and they come in various sizes and shapes and with different tool-retaining openings (Fig. 6-5). The whole unit, along with the punch or punches it holds, is secured to the holding plate with dowels and locked in this position by screws. The punch, equipped with a ball-retaining groove, is precision-located by a pressure of the spring-loaded ball.

Another help with tool guidance is that in which die shoes are aligned with precision guide pins. Four-pillar die sets were found to be the most accurately aligned instruments, surpassed only by subpress dies, which are actually considered small, self-contained, and self-aligned press units.

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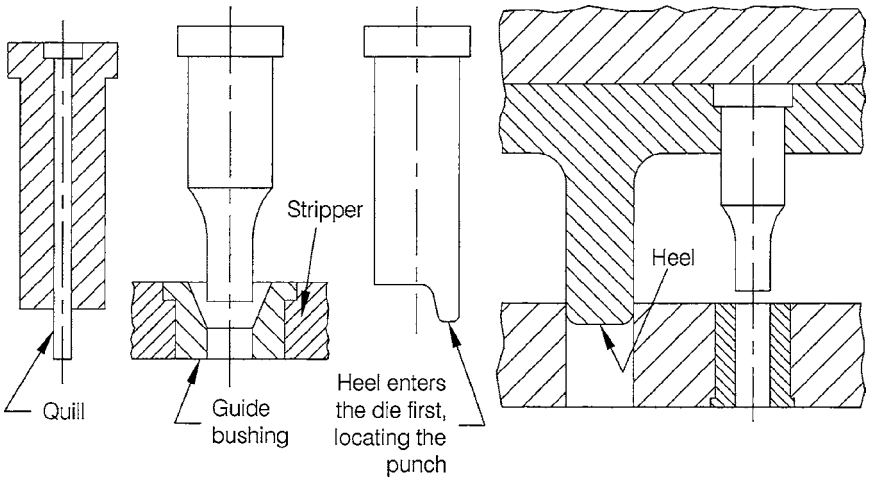

FIGURE 6-4 Support and guidance of punches.

Guide pin and pillar die sets are described in Secs. 3-1-2 and 3-1-3. Guide pins are precision-ground and fit into bushings of equal quality (Fig. 6-6). Their tolerance ranges are 0.0002 to 0.0004 in. (0.005 to 0.010 mm), and their smooth function is aided by the lubricants retained in the grooves in the bushing.

Self-lubricating bushings (Fig. 6-7) are made of high-strength bronze material, where a lubricant is embedded throughout its structure. Such a lubricating arrangement usually lasts the entire life of the bushing.

However, the absolute of the die alignments is the ball-bearing bushing (Figs. 6-8 and 6-9), which runs so tight that the effect of the side-oriented force on the tooling is almost eliminated.

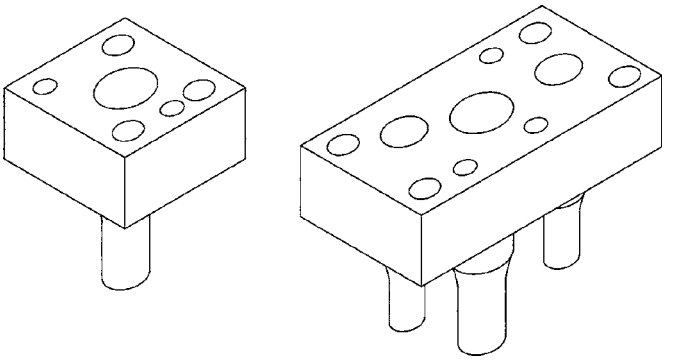

FIGURE 6-5 Punch retainer.

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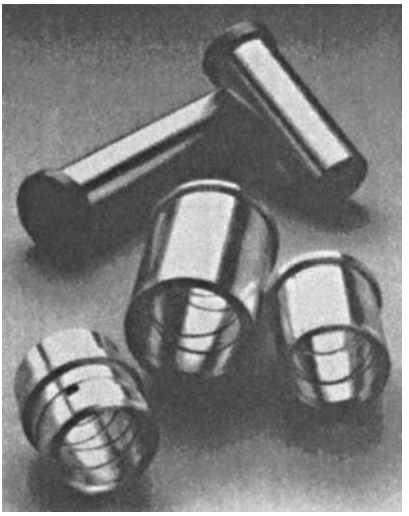

FIGURE 6-6 Guide bushings and pins. Internal grooves are for distribution of lubricant. (*Reprinted with permission from LAMINA, Inc., Royal Oak, MI.*)

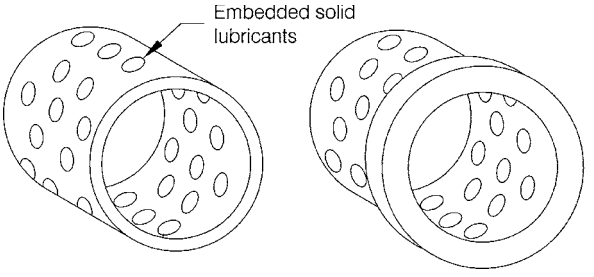

FIGURE 6-7 Self-lubricating bushings.

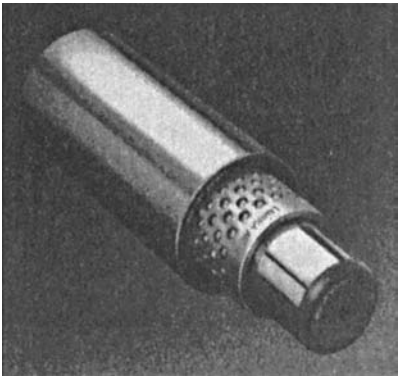

FIGURE 6-8 Ball bearing bushing assembly. (*Reprinted with permission from LAMINA, Inc., Royal Oak, MI.*)

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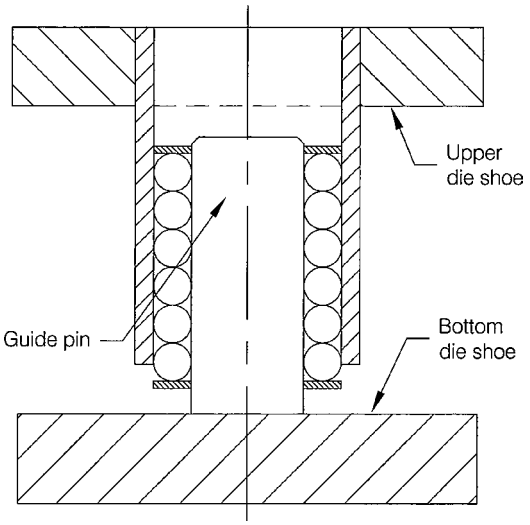

FIGURE 6-9 Ball bearing bushing cross-section.

6-4 DESIGN OF CUTTING TOOLS

The shape, size, and operating sequence of cutting tools should be redesigned to achieve a trouble-free production of high-quality parts. Sometimes tooling shapes may be modified to become more sturdy and durable, with no resulting changes to the cut part whatsoever. During the die design stage, the operating sequences should be carefully scrutinized for possible defect-causing areas. By purposeful and cautious examination of all tooling and its combinations, perfect parts will certainly be produced.

6-4-1 Length of Cutting Tools

All cutting tools must be designed in such a way that the pressure applied toward their mass will not cause their buckling or outright distortion. For that reason, their lengths must be evaluated with regard to the necessity of their support.

6-4-1-1 Cutting Punches. Basic length requirements for cutting punches made of heat-treated steels are

$$\frac{L}{\sqrt{I_{\min}/A}} > K \tag{6-1}$$

where $I_{\min}$ = moment of inertia, minimal ($I = {}^1/_2\, mr^2$ for cylinders)
L = length of the punch (see Fig. 6-10)
A = area of the punch cross-section
K = 2.385 for an inch-denominated system and 90.0 for metric system

For non-heat-treated steel material the result of formula (6-1) must be greater than 2.785.

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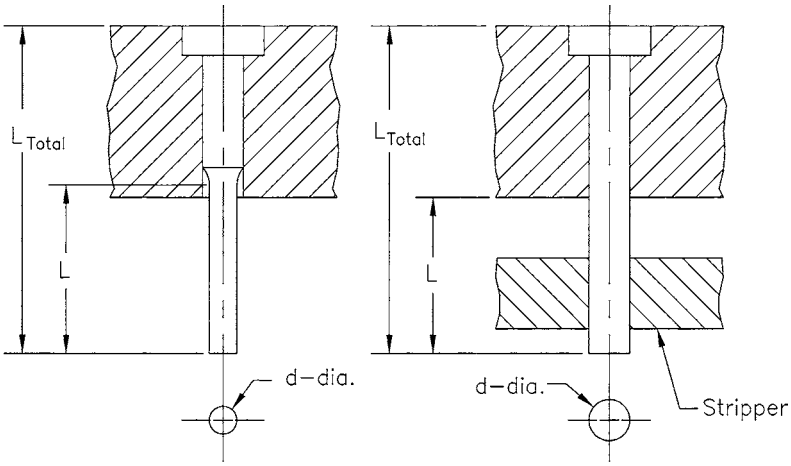

FIGURE 6-10 Length of a punch.

A mean value of pressure force should be used in all calculations, even though the cutting stress varies with its distance off the cutting edge. Mean compression strength S_{MC} is therefore expressed as a ratio of the cutting pressure and the area of the punch face:

$$S_{MC} = \frac{P}{A} = \frac{\pi dt S_{SH}}{\pi d^2/4} \tag{6-2a}$$

where P = pressure, cutting, lb (kg)
A = area of the punch face, in.^{2} (mm^2)
S_{SH} = shear strength of the punch material
t = material thickness, in. (mm)
d = punch diameter, in. (mm)

An adjusted expression of Eq. (6-2*a*) is

$$\frac{t}{d} \le \frac{S_{S-\text{lim}}}{4S_{SH}} \tag{6-2b}$$

where $S_{S-\text{lim}}$ = allowed pressure limit against the punch support.

Critical-buckling pressure may be figured using Euler's formula:

$$P_{crit} = \frac{\pi^2 EI}{4L^2} \tag{6-3a}$$

where E = modulus of elasticity
I = moment of inertia (minimal)
L = length of the punch (see Fig. 6-10)

Further the critical pressure should be made equal to

$$P_{crit} = CP \tag{6-3b}$$

where C = safety factor; C = 2 to 3 for heat-treated steel; C = 4 to 5 for non-heat-treated steel.

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BLANKING AND PIERCING OPERATIONS

Subsequently the critical length of an unguided round punch can be calculated:

$$L_{\text{crit}} = \sqrt{\frac{\pi^2 EI}{4CP}} \tag{6-4a}$$

The slenderness ratio $(L/d)_{\text{min}}$ may be calculated by using the formula

$$(L/d)_{\text{min}} = \frac{\pi}{8}\sqrt{\frac{E}{S_{S-\text{lim}}}} \tag{6-5}$$

The critical-buckling pressure for the guided punch is given by the relationship

$$P_{\text{crit}} = \frac{2\pi^2 EI}{2} \tag{6-3c}$$

and

$$P_{\text{crit}} \le CP \tag{6-3d}$$

The maximum length allowed for a round, guided punch will be

$$L_{\text{crit}} = \sqrt{\frac{2\pi^2 EI}{nP}} \tag{6-4b}$$

where n = exponent of strain hardening tendency of sheet-metal material, 0.2 to 0.5 in normal conditions, not involving superplasticity or ultrasound.

The critical slenderness ratio will subsequently become

$$\left(\frac{L}{d}\right)_{\text{min}} = \frac{\pi E}{S_{S-\text{lim}}} \tag{6-6}$$

6-4-1-2 Die Bushings. Die bushings may be compared to a thick cylinder, with an equally distributed pressure against the cutting opening. A rough height of the die button may then be calculated with the formula:

$$h \ge \sqrt[3]{P_{\text{max}}} \tag{6-7}$$

Height of the round die with a round opening may be assessed with the aid of Eq. (6-8*a*). The bending tension S_{SB} may be calculated as

$$S_{SB} = \frac{1.5P}{h^2}\left(1 - \frac{d_1}{1.5d_2}\right) \tag{6-8a}$$

where P = pressure, cutting, lb. Other values are per Fig. 6-11.

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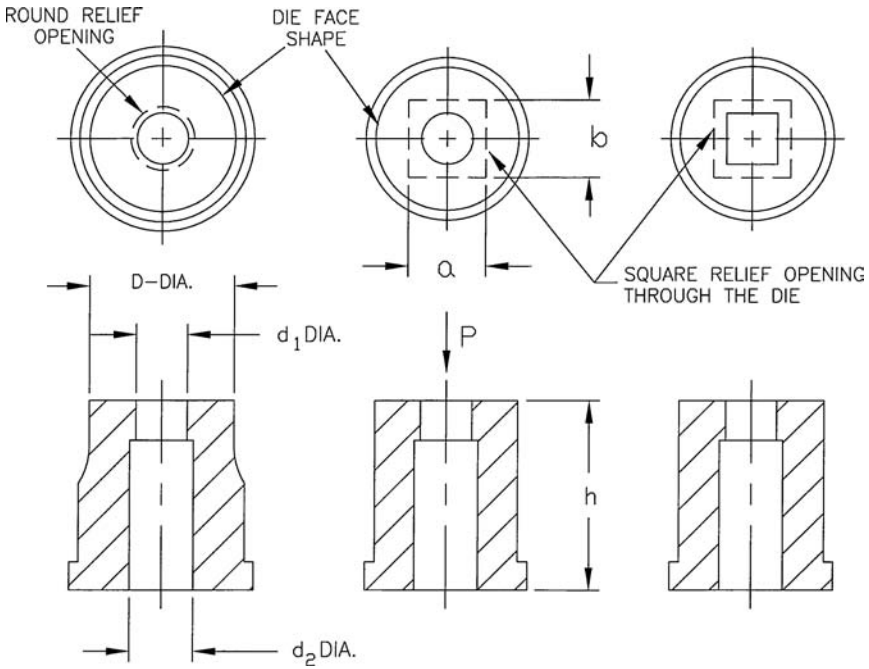

FIGURE 6-11 Dimensioning of a die.

A groomed height of the die will become

$$h \geq \sqrt{\frac{1.5P}{S_{SB-\text{lim}}}\left(1-\frac{d_1}{1.5d_2}\right)} \tag{6-9a}$$

where $S_{SB-\text{lim}}$ = allowed bending pressure limit.

A relationship must apply:

$$S_{SB} \leq S_{SB-\text{lim}} \tag{6-8b}$$

For a square or rectangular die with a round-cutting opening (see Fig. 6-11), the bending stress S_{SB} will be

$$S_{SB} = \frac{1.5P}{h^2} \tag{6-8c}$$

and the height

$$h = \sqrt{\frac{1.5P}{S_{SB-\text{lim}}}} \tag{6-9b}$$

With rounded punches with a square or rectangular-cutting opening, the formula will apply:

$$S_{SB} = \frac{3P}{h^2}\frac{b/a}{1+b^2/a^2} \tag{6-8d}$$

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or

$$h \geq \sqrt{\frac{3P}{S_{SB-\text{lim}}} \frac{b/a}{1+b^2/a^2}} \tag{6-9c}$$

A side-oriented force against the die button may be evaluated as

$$P = P_N - P_F - P_C \tag{6-10}$$

where P_N = value of the side-oriented material pressure, equal to approximately 0.1 to 0.4 of the cutting force P
P_F = force of friction between the die button and its support. A coefficient of friction $\mu = 0.15$ may be used with steel
P_c = force depending on the pressure needed to push the slugs through the die. This force is

$$P_c = P_{c-\text{act}}\, lt \tag{6-11}$$

where $P_{c-\text{act}}$ = pressure needed to push the slugs through the die
l = linear length of the cut opening
t = material thickness

6-4-1-3 Dowel Pins. Dowel pins are used to secure blocks against side shifting. If a side-acting force (or shear force) is applied toward their length, it may deform them, with subsequent damage to the block, cutting tools, and the whole die. The maximum allowed amount of such a force may be taken as

$$P_{\max} = 0.4 S_{C-\text{lim}} D_{DP}^2 \sqrt{\frac{S_{SB-\text{lim}}}{S_{C-\text{lim}}}} \tag{6-12}$$

where D_{DP} = diameter of dowel pin
$S_{C-\text{lim}}$ = allowed pressure limit against the dowel pin support
$S_{SB-\text{lim}}$ = allowed bending pressure limit

The length of the dowel pin L_{DP} will be given by the relationship

$$L_{DP} = 0.77 D_{DP} \sqrt{\frac{S_{SB-\text{lim}}}{S_{C-\text{lim}}}} \tag{6-13}$$

6-4-2 Shape of Cutting Tools

With round-cutting tools, their face surfaces may sometimes be tapered (i.e., sheared), which will somewhat reduce the demand for cutting force needed otherwise. The reasoning behind this statement is logical: As the punch cuts the metal in stages, the smaller amounts of press force are used, spread over an extended period of time.

This method of lowering the demand for press force can be of help in dies where the total cutting force will exceed or be too close to the total available press force. At the moment when all punches begin their penetration of the material, the surge wave of needed press force may be excessive to the equipment. By offsetting some large cuts, a postponement of the demand is achieved.

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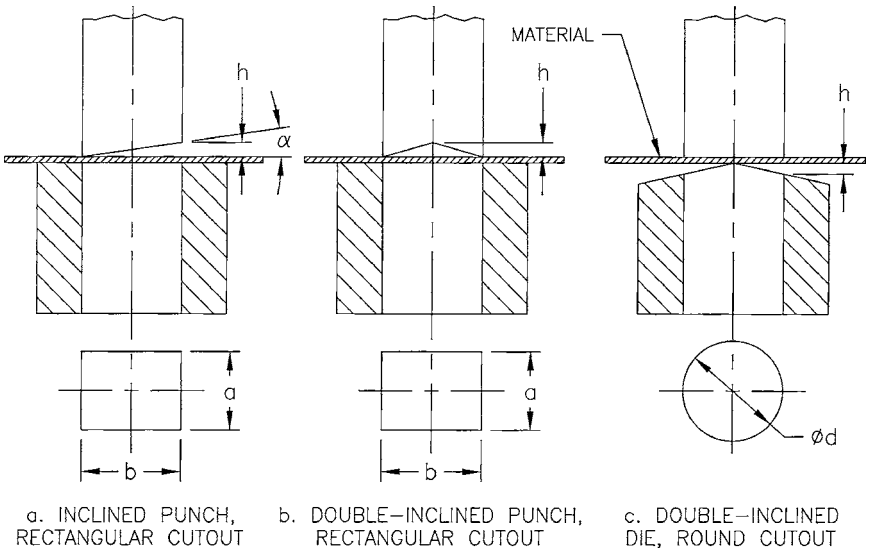

FIGURE 6-12 Sheared punches.

6-4-2-1 Inclined Punch or Die Surface. Applying a shear to the face of the tool is one of the methods used to reduce the necessary cutting pressure. The punch is simply ground under an angle, which would allow for its longest portion to begin cutting first, with the rest of the tool to follow (Fig. 6-12).

Such an arrangement is unfortunately very crude, since the shearing process is not centralized around the tool axis, but rather side shifting away from the center of the tool. A better approach is to shear the punch (or die) toward the center from all the sides, as shown in Fig. 6-13*b*, *e*. The inclination of surface, being center-oriented, will produce a centered-cutting process, with cutting forces more evenly spaced around the punch.

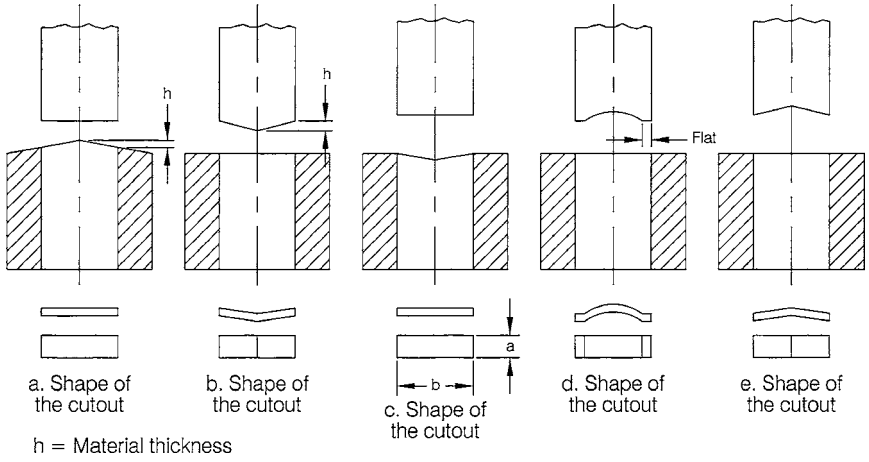

FIGURE 6-13 Punch and die shear.

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Either the punch or the die can have its cutting surfaces sloped, the amount of shear to be equal to the material thickness, with some thin materials using 1.5*t*.

Since the cut-out part or slug will always somewhat resemble the shape of the punch, it is advisable to apply the shear to that part of the tooling, which will constitute the scrap. This way the punch will be sheared if piercing, and the die will be sheared when used for blanking.

The *C method* of tool face alteration, shown in Fig. 6-13*c*, where a slight inclination is produced on the die button, is considered preferable, since the punch here enters the material at both ends of the cut simultaneously, centering itself within the die opening.

6-4-2-2 Inclined Punches Used To Retain The Material. In some cases the slanted face surface of punches may be utilized as a stock holder as well. A sample of such an arrangement is shown in Fig. 6-14.

6-4-2-3 Radiused Tooling for Exact Cutting. Rounding of the cutting edges of a punch or a die is used where a smooth, straight edge of the cut is desired. The material when pushed down by the punch is compressed before the separation, and squeezed (or extruded) through the die opening afterwards. The operation actually resembles that of cutting, combined with burnishing.

The press force has to be approximately 15 percent higher than that used for cutting with straight, nonradiused edges. The best materials to be used for this process are those with greater formability.

A rounded punch should be used for blanking and a rounded die for piercing operations. The tooling clearance can be calculated using Eq. (6-18).

$$CL_{\text{side}} = ct\sqrt{S_s} \tag{6-14}$$

where S_s = shear strength of material. See Table 6-4
t = material thickness
C = constant, for material thickness up to 0.125 in. (3.2 mm), c = 0.000174; for material thickness over 0.125 in. (3.2 mm), c = 0.000133

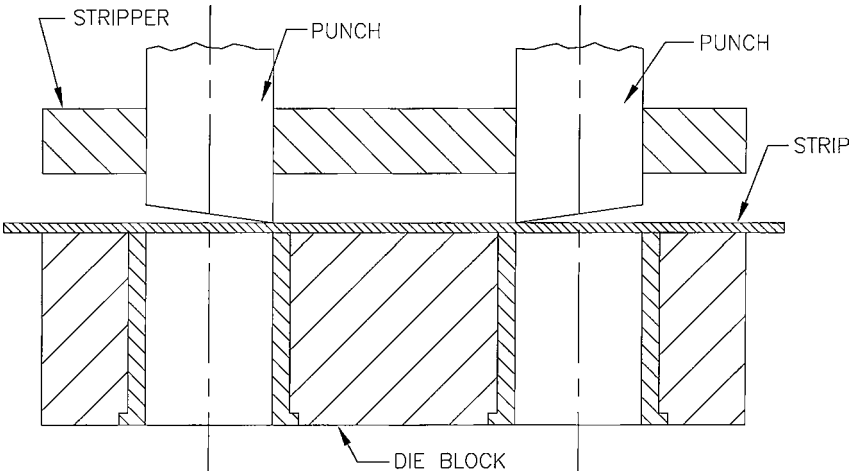

FIGURE 6-14 Punches as blankholders.

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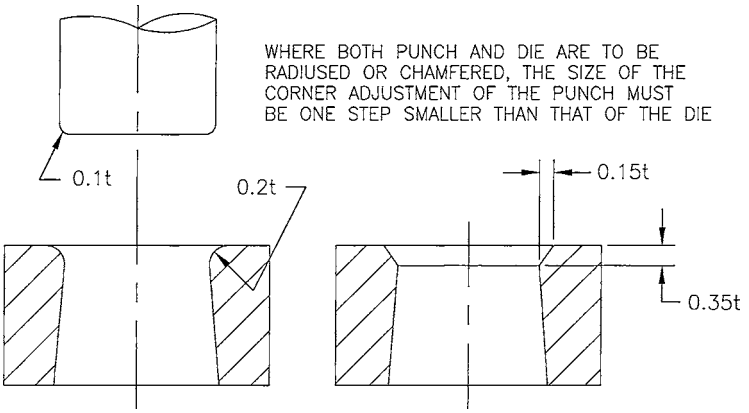
WHERE BOTH PUNCH AND DIE ARE TO BE RADIUSED OR CHAMFERED, THE SIZE OF THE CORNER ADJUSTMENT OF THE PUNCH MUST BE ONE STEP SMALLER THAN THAT OF THE DIE
0.1t
0.2t
0.15t
0.35t

FIGURE 6-15 Corner treatment of the radiused cutting punch and die.

In some cases, where a perfect finish of the cut edge is demanded, a die with a negative amount of cutting clearance can be used, as shown in Fig. 6-15. In such a configuration, the punch is actually bigger than the die opening through which the pierced part is squeezed.

A similar type of tooling, called "slug-free die" is shown in Fig. 6-16. Here the cutting occurs around the edge of the die with some burnishing influences in tandem. The punch and die both have a clearance, for the punch has to exceed the downward pitch and push the cut material down.

6-4-2-4 Shaped Punch. A method of grinding the cutting surface of a punch into a cone-shaped form may be used where some heavy piercing or piercing of hard material is to be done Fig. 6-17. On coming to contact with the metal material, the point pushes down on it, holding it in a fixed position. Some stretching of the sheet is present when the metal is pulled down by the punch before it is sheared off on contact with the die. A certain amount of thinning of the cut part's edge surface may be expected.

6-4-2-5 A Half-Twist Shape. A spiral shape added to the punch (from its two opposite sides, as shown in Fig. 6-18) may be used to offset the cutting pressure somewhat. As the punch slides down, its cutting is done in stages, following the inclined line of the spiral shape as it comes into contact with the material and the die.

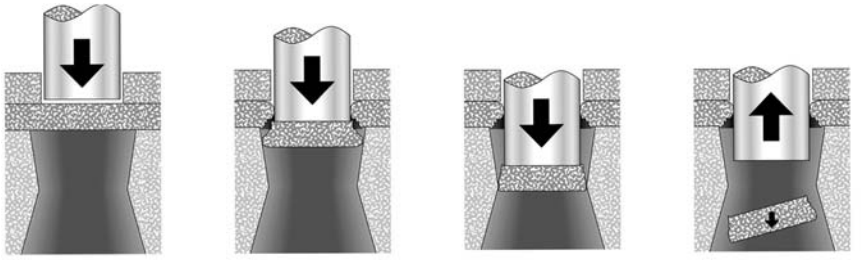
Material held securely by stripper before punch makes contact.
Punch penetrates the material. Slug fractures away from sheet.
Pressure point constricts slug. Punch stroke bottoms out as slug squeezes past pressure point.
Punch retracts and slug is free to fall down and away through exit taper.

FIGURE 6-16 Slug-free die. (*Reprinted with permission from Mate Precision Tooling, Anoka, Minnesota.*)

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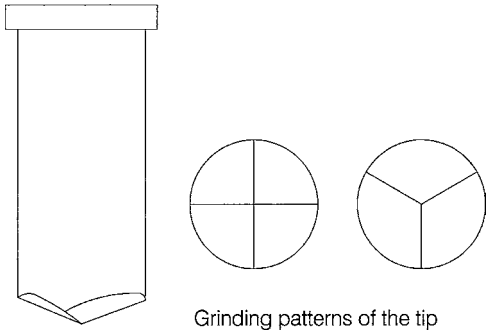

FIGURE 6-17 Grinding of the cutting surface of a punch.

Of course, all these methods of cutting surface alteration have one disadvantage in common. Such tools are quite difficult to regrind, when becoming dull in service. For that reason, flat-faced punches and dies are used more frequently, with shaped tooling being reserved for special applications.

6-4-3 Lowering the Demand for Instantaneous Press Force

When the claim of lowering the needed press force is voiced, many perhaps wonder how much can the press force be lowered. How much less can they use in their formulas? We know that lowering the press force does not apply to stripping force, which allows us to concentrate on the piercing, blanking, or trimming force only.

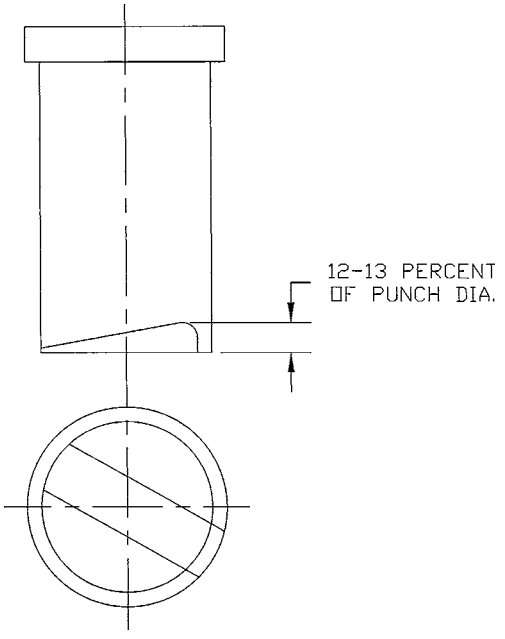

FIGURE 6-18 Spiral end of a punch.

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6-4-3-1 Cutting Force With Straight (Nonsheared) Punches. The requirement for cutting force with such tooling can be calculated on the basis of two variables: the length of the cut and the resistance of the material to tool penetration. The resistance to tool penetration depends mainly on the thickness and mechanical properties of that particular material.

With straight cutting edges, the cutting force (P) can be calculated at any given moment using the formula below.

$$P = R_c A = L_c(t - t_c)R_c \tag{6-15}$$

where R_c = resistance to cutting
A = area to be cut
L_c = length of cut, linear
t = thickness of material
t_c = depth of penetration by the tooling

The amount of permanent deformation, which is always present in fabricating operations occurs in cutting (or shearing) at the moment the shear stress reaches its maximum, and separation of the cut edge begins. With brittle materials, which suffer from lesser amounts of elasticity, the cut edge will separate sooner, already when the tool is just below its upper surface. Softer materials, high on limits of elasticity, separate hesitantly, and the cutting tool has to get to a greater depth to achieve a total cutoff.

Where we replace the resistance to cutting (R_c) with a maximum cutting strength S_c of the material, we can rewrite the above formula as:

$$P_{\max} = L_c t S_c \tag{6-16}$$

where S_c is the maximum cutting strength as per the Table 6-1.

Where the cutting surfaces become dull, the cutting force has to be increased 15 to 30 percent.

6-4-3-2 Cutting Force With Sheared Tools. When calculating the press force attributable to sheared tooling, first, the actual area of the cut must be obtained by using the formula below:

$$A\alpha = \frac{L_c t}{\tan \alpha} \tag{6-17}$$

where $A\alpha$ = area of the cut, angular
t = thickness of material
$\tan \alpha$ = angle of the sheared surface of the punch, see Fig. 6-12
L_c = length of cut, linear

TABLE 6-1 Maximum Cutting Strength of Material, S_c

Material	Maximum cutting strength, S_c
Alumunum, soft	(.75–.90) S_y
Aluminum, hard	(.60–.65) S_y
Steel	(.75–.90) S_y
Stainless steel	(.68–.72) S_y
Titanium alloys	(.65–.70) S_y

Note: Where S_y is the yield strength of the material.

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and subsequently, the cutting force will become:

$$P = A_\alpha S_y \tag{6-18}$$

where S_y is the Yield strength of the cut material.

6-4-4 Combined Tooling

Sometimes, where necessary or appropriate, two operations may be combined. Often this task is achieved by assembling two different tooling elements and making them perform two operations at the same shot. Combined operations usually follow in sequence, meaning the material is prepunched, with forming taking place right afterward.

6-4-4-1 Die Insert to Allow for Shape Cutting. Where a tool of complex shape would be needed, a combination of two or more simple segments may produce the cut of the same shape.

To build a punch shown in Fig. 6-19, in order to cut the part in a single stroke of the press would not be difficult. But to make a corresponding die, without an EDM equipment, is a completely different task. Where the punch will have the material removed, the die needs the same amount of it added.

As depicted in Fig. 6-20 the needed metal is added in the form of an insert attached to the bulk of the die with a screw.

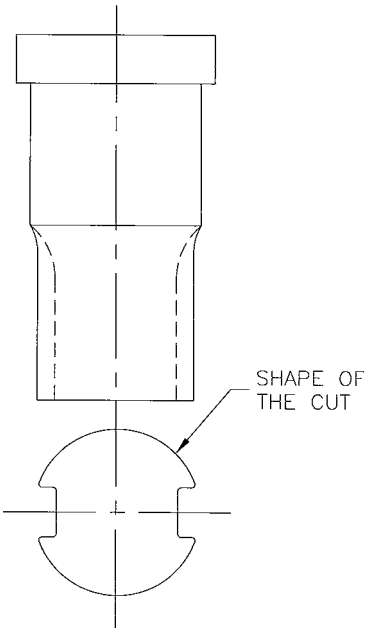

FIGURE 6-19 Shaped punch.

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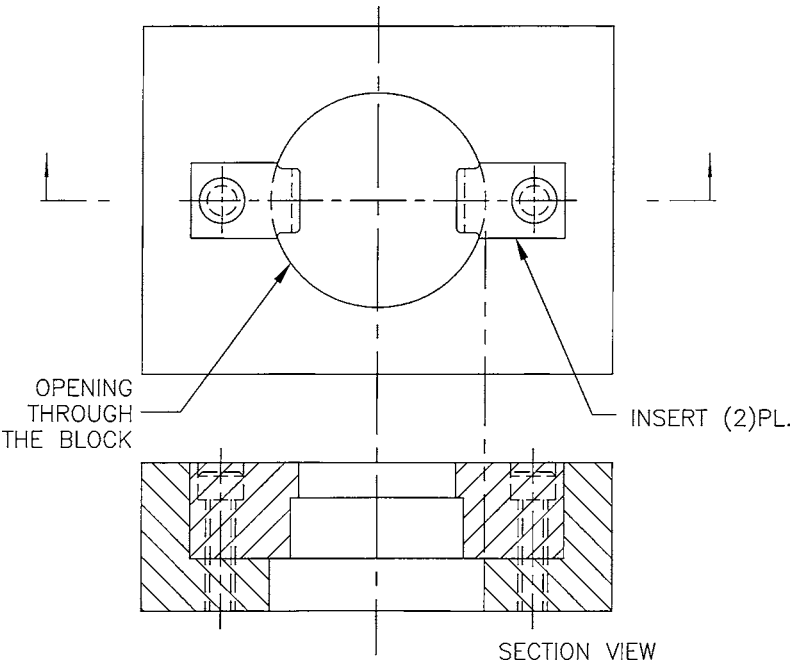

FIGURE 6-20 Die with an insert.

6-4-4-2 Drawing (or Forming) Punch With a Cutoff. The part shown in Fig. 6-21 is drawn and cut off in a single operation. During the work cycle, the material is first drawn into the required depth, equal to the height of the drawing portion of the punch. When the trimming edge comes into contact with the die, the part is cut off.

6-4-4-3 Forming and Cutting Tool. The punch shown in Fig. 6-21*b* first pierces the opening in the center; then its wider body pulls the metal along on its way down. The spring-loaded lifting pad pushes the finished part up for removal once the punch is on its way up.

6-4-4-4 Piercing and Coining of the Material. Parts may be pierced first and pressed into a predetermined die shape afterward, as shown in Fig. 6-22*a*. Often such an elaborate arrangement may be superseded by simple compression forming, shown in Fig. 6-22*b*. Here a punch enters the precut material, compressing sides of the opening to form a countersink.

Another type of compression forming is shown in Fig. 6-23. In this case, the material is unsupported in the die opening, with the punch being used for indentation purposes only.

6-4-4-5 Inclined Pressure Pad. A pressure pad with the surface of contact under an angle is used for retention of material to be cut, as shown in Fig. 6-24.

The material is not only held down by the pressure of the pad. As the cutting progresses, it is also compressed locally (around the tip of the pressure pad), which gives rise to a double-axial tension.

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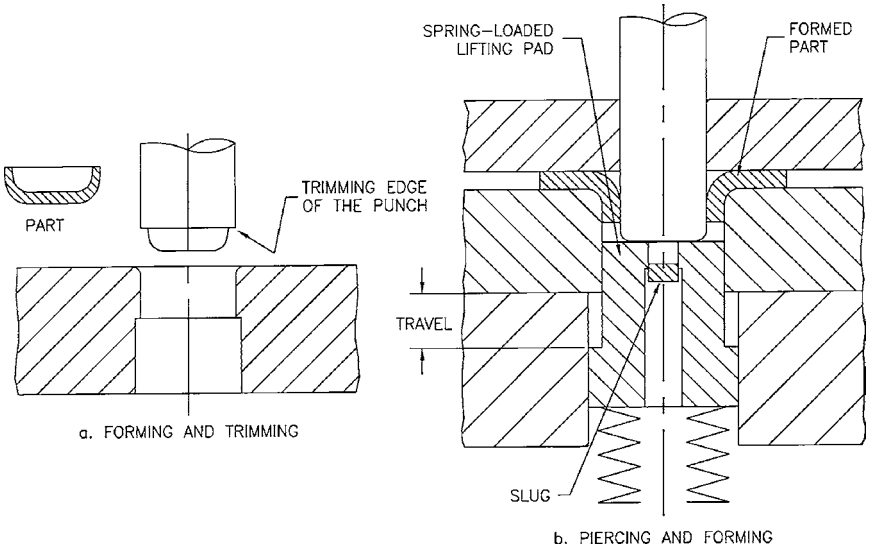

FIGURE 6-21 One-step operations.

6-4-4-6 Curling Done in a Single Operation. A one-step punch and curling tool may be used for cutting the blank and forming it to the shape shown in Fig. 6-25.

As the punch descends toward the stock, it first pierces through with its long sharp nose. While the cutting progresses, the portion of already parted material begins to imitate the shape of the punch and curls underneath it. When the flat section of the punch finally trims the part off, the curl is already formed.

6-4-5 Sequence of Operations

In order to reduce the press force necessary for cutting, sequential cutting in stages may be used. This method is quite helpful where too many cuts are to be produced in a single die.

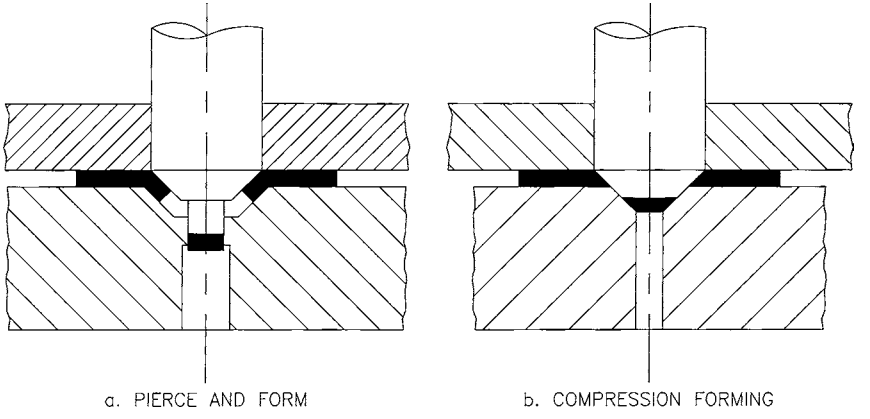

FIGURE 6-22 Forming of a recessed shape.

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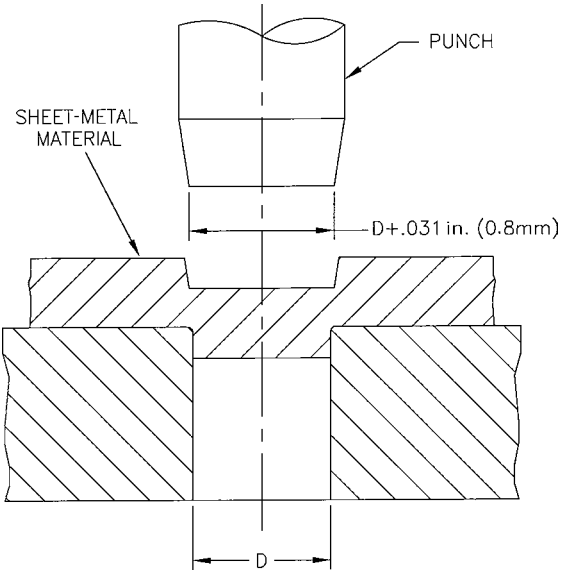

FIGURE 6-23 Forming of projections.

Each punch (as shown in Fig. 6-26) is made slightly shorter than the previous one, so that they engage the material at different times. The difference in height is recommended to be equal to such thickness of material the punch must penetrate in order to separate the cutout from the strip. Such a distance is considered 0.33*t* by some.

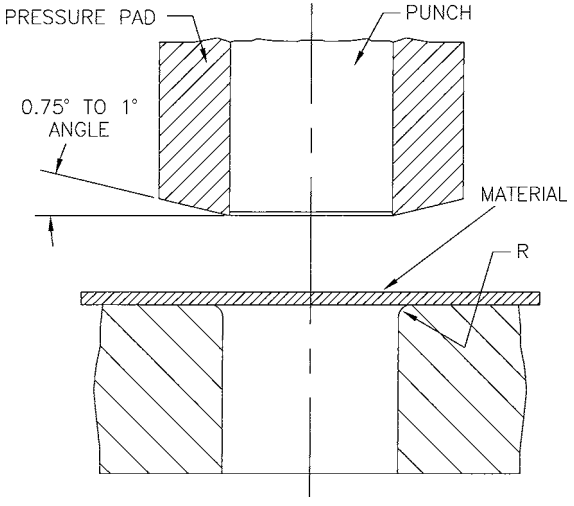

FIGURE 6-24 Inclined pressure pad.

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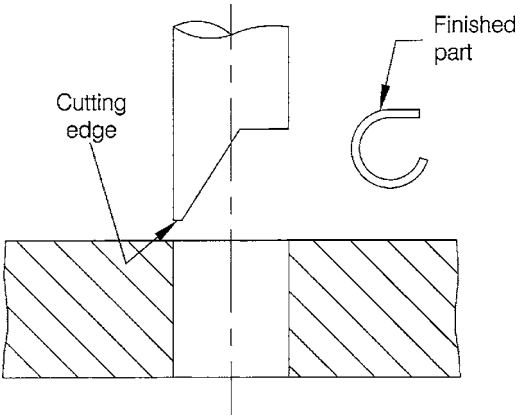

FIGURE 6-25 Cut-off and curling.

To calculate the exact cutting depth range for various materials, refer to Sec. 6-8-3, "Minimum Punch Diameter." Additionally, Table 6-2 depicts the percentage of material penetration needed to achieve severance off the strip.

The approach of sequence punching should be used where piercing of small holes occurs simultaneously with cutting of a large-sized opening. The flow of metal in such cases may be overwhelming if all punches are allowed to descend on the material at the same time. Because of the stress produced within the strip material by the activity of the large punch, all thin punches will certainly have a tendency to break.

As shown in Fig. 6-27, the large punch (or punches) should be long enough to enter the material first. When it penetrates the strip far enough to consider the part cut off, thinner punches may be allowed to follow.

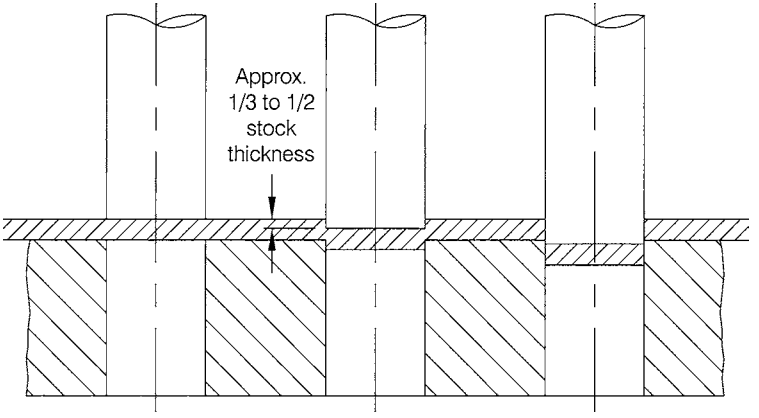

FIGURE 6-26 Offset punching.

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TABLE 6-2 Penetration of Material in Cutting

	Coefficient C_1, in %		
	Under 0.156 in. (4 mm) stock thickness	Over 0.156 in. (4 mm) stock thickness	Angle of inclination, degrees
Steel:			
Soft	45–60	35–45	3–11
Medium-hard	35–50	20–35	4–14
Hard	20–35	10–20	4–15
Aluminum:			
Soft	45–65	45	1–5
Hard	30–50	30	3–7
Brass:			
Soft	50–60	50	1–12
Hard	20–30	20	3–15

Note: Thinner materials should use a higher percentage amounts, while thicker materials should use the lower percentages.

6-5 CUTTING CLEARANCES

The amount of cutting clearance between the punch and the die is of great importance in all sheet-metal work. It is usually given as a percentage of the thickness of cut material, as shown in Table 6-3.

The cutting clearance is *always* added to the die *bushing* of the particular cutting station. The punch, as stated previously, has the exact size of the hole to be cut and a tolerance of

+0.0002 in. (+0.005 mm)
–0.0000 in. (–0.000 mm)

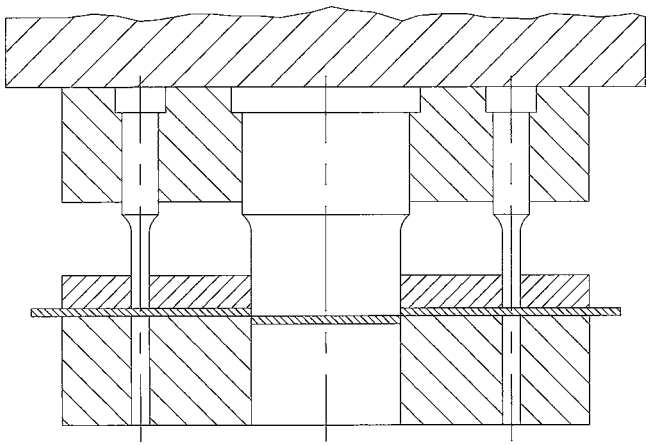

FIGURE 6-27 Combination of small and large punches.

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TABLE 6-3 Cutting Clearances in Percentages of Material Thickness Per Side

All materials, up to 0.001 in. (0.03 mm) thickness	0.0001 in. per side 0.003 mm per side
All materials, 0.001–0.025 in. (0.03–0.65 mm) thickness	5% per side
Blue steel, up to 0.025 in. (0.65 mm) thickness	
Copper, brass, soft steel,	5–8% per side
0.025 in. (0.65 mm) thick and up	5% per side, ID
Medium hard steel,	8% per side, OD
0.025 in. (0.65 mm) thick and up	6% per side, ID
Stainless steel, carbon steel, Cr-Ni steel,	9% per side, OD
0.025 in. (0.65 mm) thick and up	8% per side, ID 10% per side, OD

Note: Clearances for aluminum to be used according to its comparable hardness.

The die opening, which is to contain the punch, will use its size, add the amount of cutting clearance to it, and attach a tolerance range, often similar to that of the punch, or

$$+0.0002 \text{ in. } (+0.005 \text{ mm})$$
$$-0.0000 \text{ in. } (-0.000 \text{ mm})$$

As an example, with the punch size of

$$1.0000 \text{ in.} \begin{matrix} +0.0002 \\ -0.0000 \end{matrix} \text{ DIA}$$

in metric, this becomes

$$25.400 \begin{matrix} +0.005 \\ -0.000 \end{matrix} \text{ DIA}$$

the die opening at 8 percent cutting clearance for fabrication of $^1/_{16}$ in. (1.6 mm) thick material will be

$$1.010 \text{ in.} \begin{matrix} +0.0002 \\ -0.0000 \end{matrix} \text{ DIA}$$

and in metric,

$$25.66 \text{ mm} \begin{matrix} +0.005 \\ -0.000 \end{matrix}$$

Even though the correct cutting clearance is recommended to be somewhere between $0.08t$ and $0.10t$ per side, some manufacturers use clearances much broader, with up to $0.16t$ per side. Such a gap may often be excessive and the cuts it will produce are frequently rough and uneven. Yet, with larger-size punches and with thicker material, greater cutting clearances can be chosen with no detrimental effect on the outcome.

At the same token, manufacturers of tooling for automatic NC machinery (so-called turret presses) sometimes use extremely small clearances with impressive results. The trick is in the total guidance of the punch, which is restricted from any deviation by its precision-made sleeve, and ultimately aligned with the die, both components being firmly retained within the heavy ring of a turret. This type of tooling is built as separate little dies with small spring-loaded strippers included in every assembly.

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6-5-1 Prevention of Permanent Deformation in Cutting

All cut material is affected not only by the tooling, but also by the surrounding operations within the die. Additionally, there is the influence of the mechanical properties of the fabricated material, its thickness, the speed of the cutting process, and other variables.

In order to evaluate the possibility of the material deformation, a simple formula shown below may be used for all sheets thinner than 0.093 in. (2.5 mm).

$$f_L = ct\sqrt{S_s} \tag{6-19}$$

where f_L = deformation, maximum limit
t = thickness of pierced material
S_s = shear strength of the material
c = correction factor

The correction factor c may be used from within the range of:

0.00004 for the best surface quality of the cut

0.00030 for the least cutting force and least surface quality

Material testing has proved that all deformation limits above $0.3t$ not only cause an excessive distortion of the cut, they also exhaust the plasticity of the material in the surrounding area while altering some tensile properties as well.

6-5-2 Calculated Cutting Clearances

Cutting clearances CL may also be calculated, using Eq. (6-20) below

$$CL_{\text{side}} = ct\sqrt{S_s} \tag{6-20}$$

where t = material thickness
S_s = shear strength of material; see Table 6-4
c = constant, for materials up to 0.125 in. (3.2 mm) thick, c = 0.00012 to 0.0008, for materials above 0.125 in. (3.2 mm) thick, c = 0.00017 to 0.0010

6-6 PUNCHING AND BLANKING PRESSURE

The amount of force needed to punch out an opening in sheet metal has to be calculated in order to determine the size of a press to use.

Somewhere at the beginning stage of die design, the total amount of pressure, or tonnage, needed for carrying out all die operations has to be determined. On the basis of this tonnage, the appropriate press should be chosen, the data sheet of which supplies information concerning the maximum die size, shut height, and stroke length for further advancement of the die design.

The press tonnage should be figured out quite accurately, as the choice of a correct press size is relevant. Should a press of too low a tonnage be chosen, excessive stresses may be created during the operating process, often resulting in some sort of breakage. With too powerful a press for the given job, its extra tonnage will be inefficiently wasted, if not additionally causing damage to the press equipment.

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BLANKING AND PIERCING OPERATIONS

TABLE 6-4 Shear Strength of Material

	Lb/in-sq	MPa
Tin, rolled sheet	5,000	35
Zinc:		
Rolled sheet	18,000	125
Hard rolled	20,000	140
Copper	25,000	175
Brass, bronze	35,000	240
Aluminum:		
Soft	10,000	70
Half-hard	20,000–30,000	140–210
Full-hard	40,000	275
Steel:		
0.1% carbon, hot rolled	35,000	240
0.1% carbon, cold rolled	45,000	310
0.2% carbon, hot rolled	45,000	310
0.2% carbon, cold rolled	55,000	380
0.3% carbon, hot rolled	55,000	380
0.3% carbon, cold rolled	65,000	450
High-carbon steel	75,000–85,000	520–600
Stainless steel	70,000–100,000	500–700

Note: 2,000 lb = 1 ton

Naturally, an ideal choice would be a press having the exact or just very slightly higher tonnage than whatever is needed.

Tonnage can be calculated by using Eq. (6-21). It is assumed that no shear to either punch- or die-cutting surface is applied.

$$P_{BL(\text{lbs})} = LtS_s \tag{6-21a}$$

$$P_{BL(\text{tons})} = P_{\text{lbs}} \cdot 2000 \tag{6-21b}$$

where L = total length of a cut (or cuts)
t = material thickness
S_s = shear strength of material, per Table 6-4

In metric environment, this formula will remain as

$$P_{BL(\text{MPa})} = LtS_s \tag{6-21c}$$

The length of a cut should be a total length of all cut edges, be it straight lines or circumferential values.

6-6-1 Cutting Force With Inclined Cutting Surfaces

To obtain a cutting force, needed for the application of sheared punches and dies, a different set of formulas have to be used. For cutting with a sheared punch, such as the one shown earlier in Fig. 6-12 and 6-13, where the shape of the punch is rectangular, the following equation is applicable:

$$P_{BL} = t\left(a + 2C_1\frac{bt}{h}\right)S_sC_2 \tag{6-22a}$$

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where t = material thickness
a = shorter side of the rectangular cut (see Fig. 6-12)
b = longer side of the rectangular cut (see Fig. 6-12)
h = height of the tool's inclination
S_s = shear strength of the material
C_1 = amount of material penetration, from Table 6-2
C_2 = condition of cutting surfaces, ranging between 1.2 and 1.5

A rectangular cutout, using a punch with shear applied to its two sides, such as the one shown earlier in Fig. 6-12 and 6-13*E*, will utilize the formula

$$P_{BL} = 2t\left(a + C_1 \frac{bt}{h}\right) S_s C_2 \tag{6-22b}$$

A circular opening, with the shear applied to the die, as shown earlier in Fig. 6-13*A*, where the height of the inclined portion is equal to the material thickness, can be calculated as follows:

$$P_{BL} = \frac{2}{3}\pi dt\, S_s C_2 \tag{6-23}$$

where d is the punch diameter and $h = t$.

6-6-2 Finding the Center of Pressure of a Blanking Station

Where a compound blanking die is too large, it would better be positioned on the same axis as the ram of a press. This way the center of the press force and the center of its distribution throughout the blanking station will coincide. To position a powerful blanking station slightly off the center may result in greater than usual wear of die bushings, caused by the die's inclination in the direction of the lesser support.

In order to place a complicated shape dead on center, first the center must be located. The method of calculating the center of pressure of an irregular shape is demonstrated on the sample shown in Fig. 6-28.

First, the shape must be broken down into single lines without considering the geometrical entities they form. *X-Y* axes should be positioned in the corner of a shape to establish the zero position.

The length of each line is to be calculated, along with the distance of its center off the zero point in both x and y dimension. The length of each line should be called L, and its subscript determines the sequential number of the line.

The center of shape should then be calculated separately along each axis. The formulas are as follows:

$$X_{\text{center}} = \frac{L_1X_1 + L_2X_2 + \cdots + L_nX_n}{L_1 + L_2 + \cdots + L_n} \tag{6-24}$$

and

$$Y_{\text{center}} = \frac{L_1Y_1 + L_2Y_2 + \cdots + L_nY_n}{L_1 + L_2 + \cdots + L_n} \tag{6-25}$$

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BLANKING AND PIERCING OPERATIONS

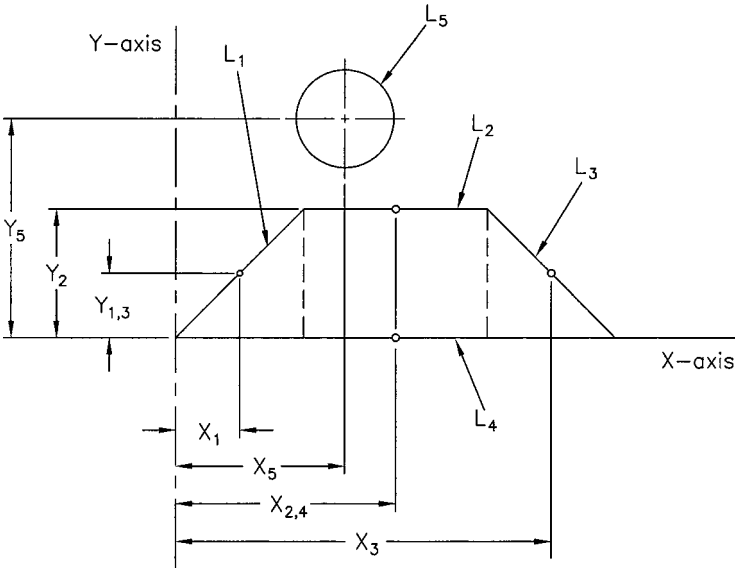

FIGURE 6-28 Center of pressure.

6-7 STRIPPING PRESSURE

A stripping pressure calculation helps to determine the correct amount of the spring pressure a spring-loaded stripper must produce. It usually varies between 3 and 20 percent of the blanking pressure and can be figured out using Eq. (6-26):

$$P_s = 3.5\ Lt \tag{6-26}$$

where all values are the same as with the blanking pressure.

The amount of delivered stripping pressure depends mainly on the proper design and proper function of springs, which are supporting the stripper's mass. The second influential factor is the thickness of processed material, which governs the demand for stripping pressure approximately as shown in Table 6-5.

The calculation above is but an approximation of the actual pressure needed to strip the part. The precise amount is very difficult to establish, since it is influenced by too many

TABLE 6-5 Stripping Pressure As Percentage of Cutting Pressure

Stock thickness, inches	Stock thickness, millimeters	Stripping pressure as percentage of cutting pressure
up to 0.042	up to 1.00	3–8
0.043–0.093	1.01–2.50	8–10
0.094–0.156	2.51–4.00	10–13
0.157–0.250	4.01–6.50	13–20

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variables. The condition of the tooling, cutting clearance, type of material, and lubrication of tooling are just several out of many factors influencing the amount of stripping pressure needed.

Sheared punches may reduce the blanking pressure, but they have no effect on the stripping pressure requirements. However, staged punching, where the height of cutting tools is offset, will produce a decrease in demand for stripping pressure. Two levels of punches would halve the amount of stripping pressure otherwise needed. Three levels of punches will use up one-third of the pressure, and so on.

6-8 SCRAP AND HOLE SIZE RECOMMENDATIONS

Blanks, when positioned on a strip, certainly should not be spaced too far apart, for a large waste of material will result. However, placing them too close to each other may create a different kind of waste, that of a ruined strip, ruined tooling, and ruined die. The proper spacing is very important, and its amount depends on the material thickness above everything else (Figs. 6-29 and 6-30).

6-8-1 Standard Scrap Allowance

The proper spacing should be established by using Table 6-6, where the values are given with regard to the material thickness.

An additional distinction according to the cut material is provided in Table 6-7.

Openings, when punched too close to the edge, may produce bulging and distortion. However, where the holes must appear closer to the edge than recommended and a design change cannot be enforced, punching the openings first and subsequently producing the edge cut-off will certainly eliminate the part's tendency to distortion.

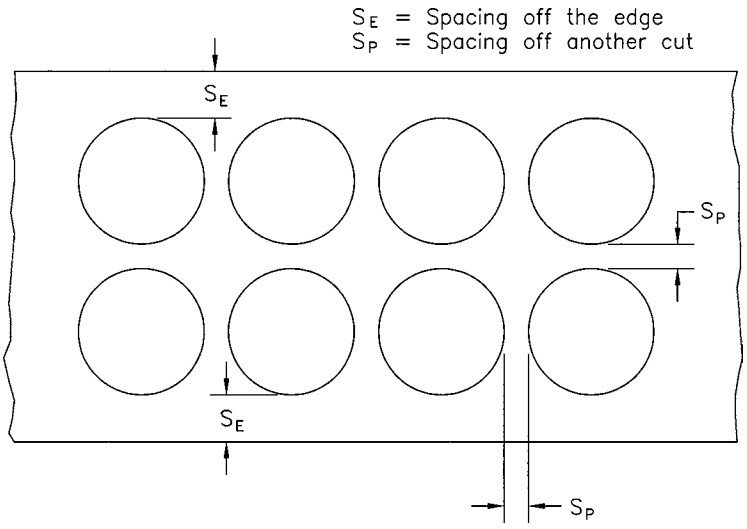

FIGURE 6-29 Distances between parts on sheet.

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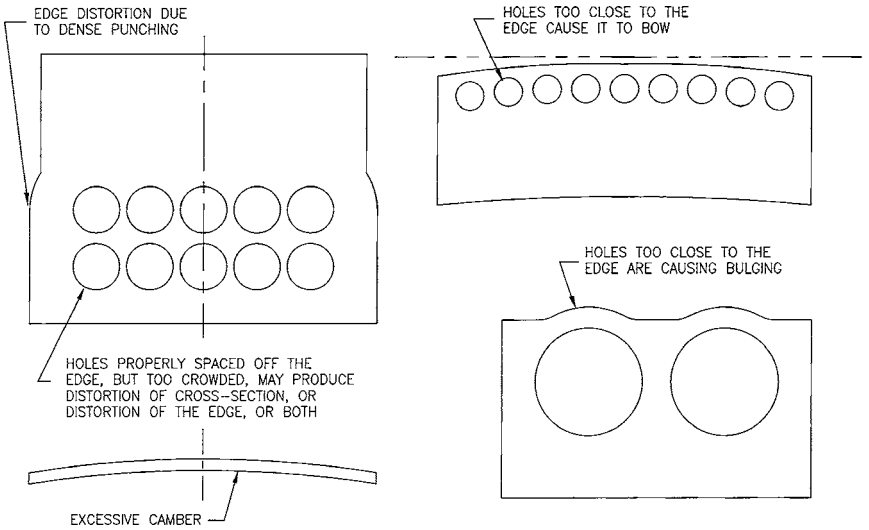
EDGE DISTORTION DUE TO DENSE PUNCHING
HOLES TOO CLOSE TO THE EDGE CAUSE IT TO BOW
HOLES TOO CLOSE TO THE EDGE ARE CAUSING BULGING
HOLES PROPERLY SPACED OFF THE EDGE, BUT TOO CROWDED, MAY PRODUCE DISTORTION OF CROSS-SECTION, OR DISTORTION OF THE EDGE, OR BOTH
EXCESSIVE CAMBER

FIGURE 6-30 Holes in relation to the edge of the part.

6-8-2 Practical Scrap Allowance

Arthur Seltmann came up with several rules for minimum spacing of blanks on the strip. These are as shown in Figs. 6-31 through 6-33. The values given were developed for a spring stripper only; where a bridge stripper is used, an increase in spacing is necessary.

Some additional advice: when designing a trim punch, the thinnest section of it must be at least 1.5*t* and never less than $^1/_8$ in. (3.2 mm). Where the length of the cut is longer than

TABLE 6-6 Scrap Allowance in Multiple Parts

	Allowance ranges for metals	
	S_P value	S_E value
Material thickness:		
Up to 0.031 in. (0.8 mm) thick	0.031 in. (0.8 mm)	0.062 in. (0.8 mm)
0.031–0.062 in. (0.8–1.6 mm) thick	*t*	0.062 in. (0.8 mm)
0.062 in. (1.6 mm) and up	*t*	*t*
The minimal S_P value may change with different materials:		
Medium-hard steel	0.031 in. (0.8 mm)	
Hard steel	0.035 in. (0.9 mm)	
Bronze, hard brass	0.045 in. (1.1 mm)	
Other brass	0.048 in. (1.2 mm)	
Aluminum	0.055 in. (1.4 mm)	
Plastics	0.062–0.078 in. (0.8–2.0 mm)	

Note: Considering these variations in the minimal required distance between parts, the Sp and Se values will have to be adjusted for the percentage difference attributable to the material change.

t = material thickness
S_P = space between parts
S_E = space off the edge

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TABLE 6-7 Scrap Allowance for Blanking

Material	When length of skeleton segment between blanks or along edge is equal to or less than $2t$			When length of skeleton segment between blanks or along edge is equal to or greater than $2t$		
	Thickness of stock, t	Edge of stock to blank	Between blanks, same row	Thickness of stock, t	Edge of stock to blank	Between blanks, same row
Metals, general: Standard strip stock	Under 0.021 in. (0.5mm) 0.022–0.055 in. (0.5–1.5 mm) Above 0.55 in. (1.5 mm)	0.050 in. (1.3 mm) 0.040 in. (1.0 mm) $0.7t$	0.050 in. (1.3 mm) 0.040 in. (1.0 mm) $0.7t$	Under 0.044 in. (1.1 mm) Above 0.044 in. (1.1 mm)	0.050 in. (1.3 mm) $0.9t$	0.050 in. (1.3 mm) $0.9t$
Extra-wide stock and weak scrap skeleton	Under 0.042 in. (1.1 mm) Above 0.042 in. (1.1 mm)	0.060 in. (1.5 mm) $1.4t$	0.050 in. (1.3 mm) $1.2t$	Under 0.033 in. (0.85 mm) Above 0.033 in. (0.85 mm)	0.060 in. (1.5 mm) $1.8t$	0.050 in. (1.3 mm) $1.6t$
Stock run through twice	Under 0.042 in. (1.1 mm) 0.043–0.055 in. (1.1–1.5 mm) Above 0.055 (1.5 mm)	0.060 in. (1.5 mm) $1.4t$ $1.4t$	0.050 in. (1.3 mm)† 0.040 in. (1.0 mm) $0.7t$	Under 0.033 in. (0.85 mm) 0.034–0.044 in. (0.85–1.1 mm) Above 0.044 in. (1.1 mm)	0.060 in. (1.5 mm) $1.8t$ $1.8t$	0.050 in. (1.3 mm)† 0.040 in. (1.0 mm) $0.9t$
Stock run through twice and first and second row of blanks interlock	Under 0.042 in. (1.1 mm) Above 0.042 in. (1.1 mm)	0.060 in. (1.5 mm) $1.4t$	0.050 in. (1.3 mm)* $1.4t$†	Under 0.033 in. (0.85 mm) Above 0.033 in. (0.85 mm)	0.060 in. (1.5 mm) $1.8t$	0.050 in. (1.3 mm)* $1.8t$†
Steel (silicon, spring, stainless)	Under 0.042 in. (1.1 mm) Above 0.042 in. (1.1 mm)	0.060 in. (1.5 mm) min. $1.4t$	0.060 in. (1.5 mm) min $1.4t$	Under 0.033 in. (0.85 mm) Above 0.033 in. (0.85 mm)	0.060 in. (1.5 mm) min. $1.8t$	0.060 in. (1.5 mm) min. $1.8t$

*Allow 0.060 in. (1.5 mm) between blanks at first and second rows.
†Allowance between blanks in the same row and also between blanks of first and second rows.
Source: After Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from The McGraw-Hill Companies.

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Allowance for Straight Cuts
(T is one thickness of material)

1. Length of cut
   of less than 5 T .....1 T min.
2. Length of cut
   between 5 T and 10 T .....1.5 T min.
3. Length of cut
   between 10 and 20 T .....2 T min.
4. Length of cut
   greater than 20 T .....3 T min.

Allowance for Shaped Cuts

5. Sharp corners
   or small radii .....0.5 T min.
6. Large radii
   or curves .....1 T min.

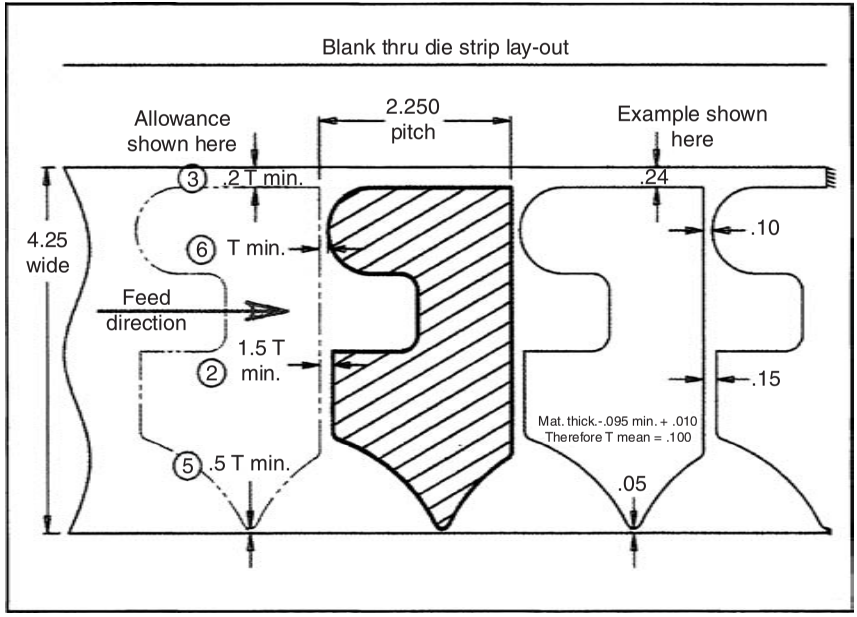
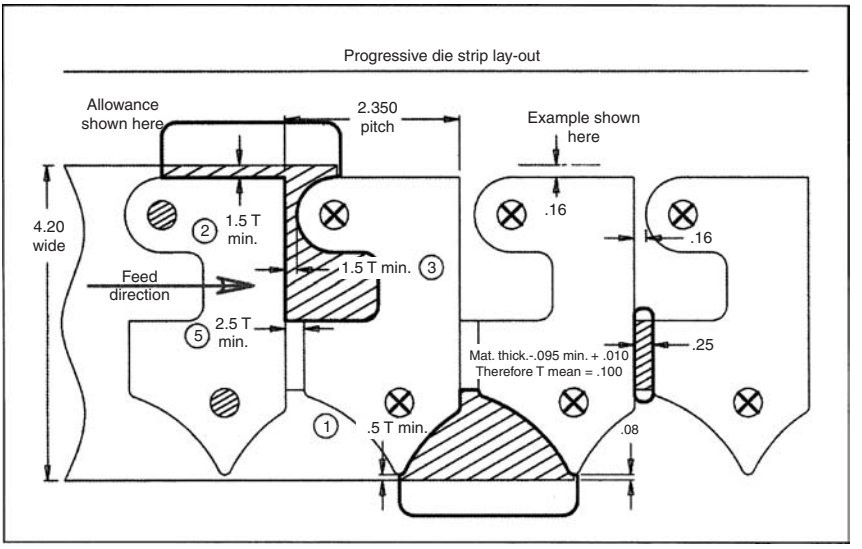


FIGURE 6-31 Trim allowance for a blank through die. (*From: Art Seltmann, American Tool, Die & Stamping, November/December 98. Reprinted with permission from Eagle Publications, Novi, Michigan.*)



Allowance for a Progressive Die (T is one thickness of material)

1. Radius trim to the edge of material .....0.5 T because the punch extends beyond.
2. Straight trim to edge .....1.5 T min. since scrap may cause burrs on part.
3. Thinnest part of punch .....1.5 T min. for curved or rounded trims.
4. Thinnest part of punch.....2.0 T min. for straight trims and/or sharp corners.
5. A thin straight punch.....2.5 T min. (like the cut-apart punch shown)

Note: The minimum diameter for a round pierce punch is 1.5 T, unless it is guided or a straight ground, in which case a whip-sleeve punch is used. This also applies to most classified shapes.

FIGURE 6-32 Trim allowance for a progressive die (a.k.a. Trim or notch & cut-apart die) (*From: Art Seltmann, American Tool, Die & Stamping, November/December 98. Reprinted with permission from Eagle Publications, Novi, Michigan.*)

10 times its width, the width of the punch should be increased to a minimum of three material thicknesses, for strength. A round piercing punch must always be a minimum of 1.5*t* in diameter.

6-8-3 Minimum Punch Diameter

The old saying that the minimum hole diameter should be equal to the material thickness may not be true in all cases. The reason for a discrepancy is that this rule often ignored additional variables such as the material shear strength and the compressive strength of the punch. Actually, the minimum punch diameter must be within such a range that the compressive strength of the punch material will be greater than the force needed to punch the opening.

The maximum allowable compressive stress S_c of the punch depends on the type of material used, its hardness, and other qualities. A tool grade steel, oil hardened and shock resistant, will take about 300,000 lb/in.^{2} (2070 MPa) before it will break. Therefore, a safe range of 200,000 lb/in.^{2} (1380 MPa) can be easily assumed, with regard to the extended tooling life.

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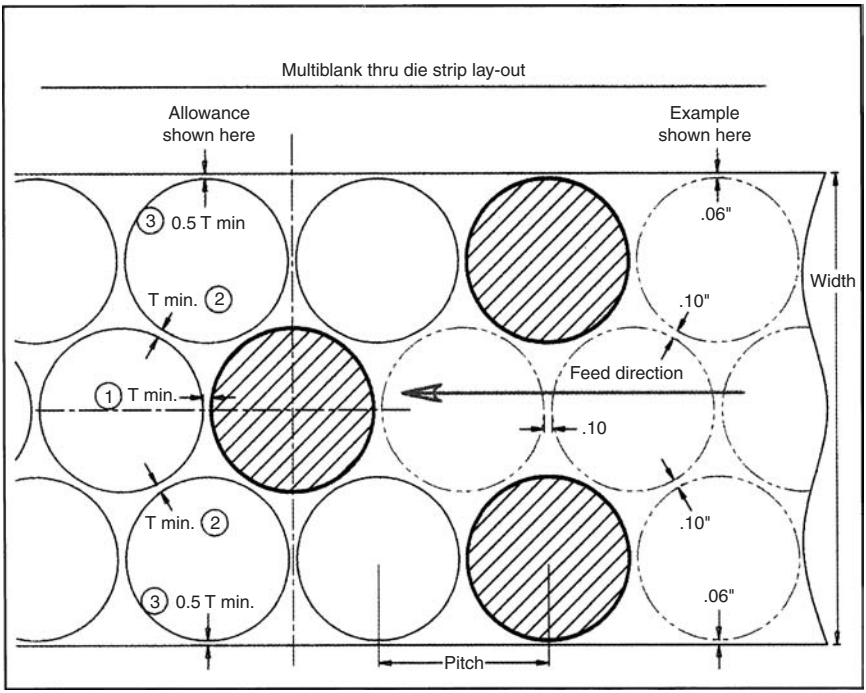

Allowance for Multiblank thru Die

1. Between Blanks with pitch .....T min.
2. Between Blanks diagonally .....T min.
3. Blank to the Edge of Material ..... 0.5 T min. because if there were a problem, the width of material used could easily be increased.

FIGURE 6-33 Allowance for a multi-blank through die. (*From: Art Seltmann, American Tool, Die & Stamping, November/December 98. Reprinted with permission from Eagle Publications, Novi, Michigan.*)

With the shear strength of the material known, the punch diameter can be easily figured out by using the graph in Fig. 6-34. Otherwise for exact calculation, Eq. (6-27) must be used to evaluate the maximum compressive stress on the punch

$$S_c = \frac{tS_sL}{A} \tag{6-27}$$

where S_c = compressive stress in the punch
S_s = shear strength of the punched material
t = material thickness
L = length of the cut, in
A = cross-sectional area of the punch, calculated per condition in Fig. 6-35

The result should be compared with the chart in Fig. 6-36. The minimal hole size should be read off the chart, with regard to the given material thickness.

To use the graph from Fig. 6-36, the thickness of the material has to be located on the vertical scale. Follow its line horizontally up to the lower edge of the area representing the

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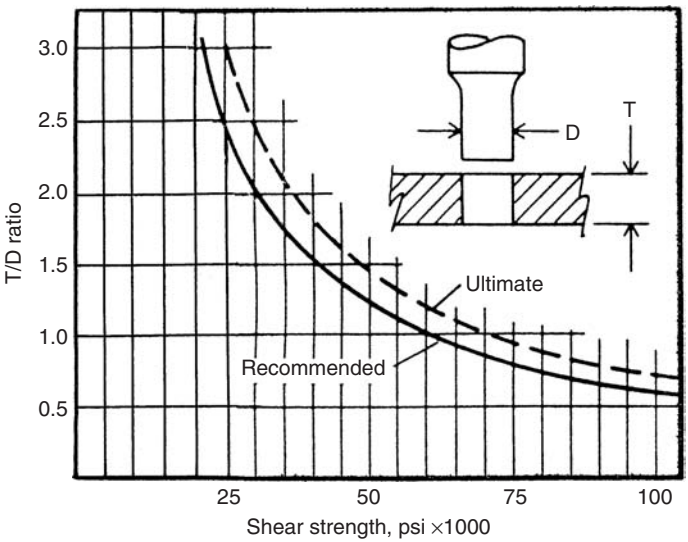

FIGURE 6-34 Ratio of material thickness to the punch diameter as a function of shear strength. (*From: O.D. Lascoe*, "Handbook of Fabrication Processes," *published by ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

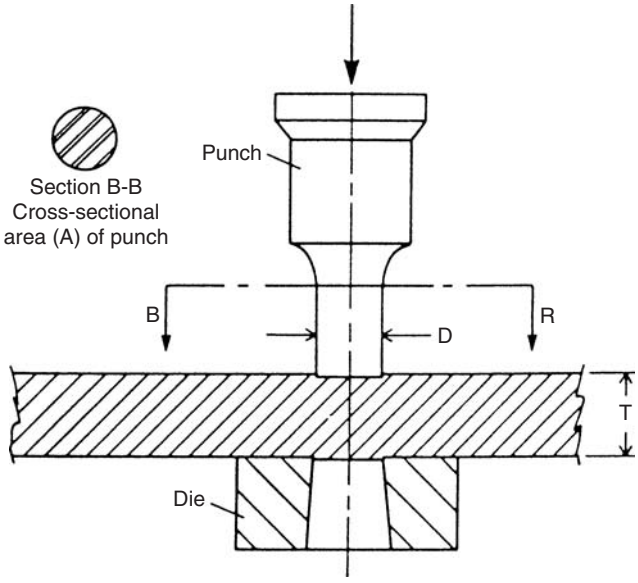

FIGURE 6-35 Punch diameter to material thickness. (*From: O.D. Lascoe,* "Handbook of Fabrication Processes," *published by ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

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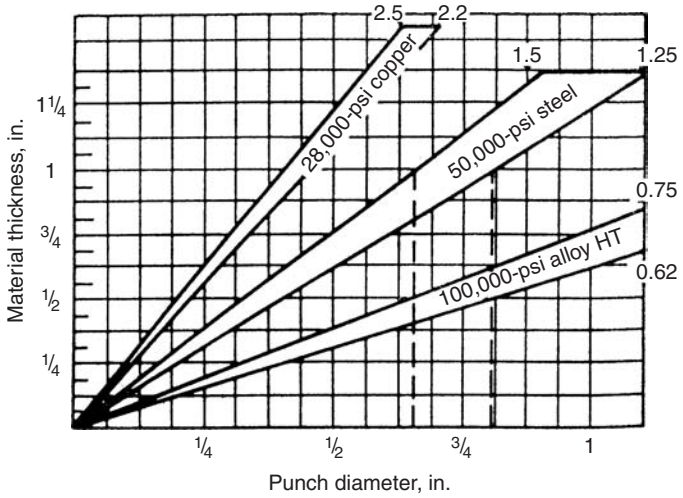

FIGURE 6-36 Minimum punch diameter (hole size) as a function of material thickness. (*From: O.D. Lascoe*, "Handbook of Fabrication Processes," *published by ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

material to be pierced. From the point of intersection, the corresponding punch diameter size can be read below.

The upper edge of each material's area represents the breaking range of the punch.

An overloaded punch will expand in size as its elastic limit is exceeded. An increased stripping force will have to be applied against such a tool, which will actually cause its breakage. Some punches may buckle under a load, breaking afterward.

Supported punches such as those shown in Figs. 6-37 and 6-4 will not fail as described. These tools would perform well up to a thickness-to-diameter ratio of 2:1 when piercing the mild steel.

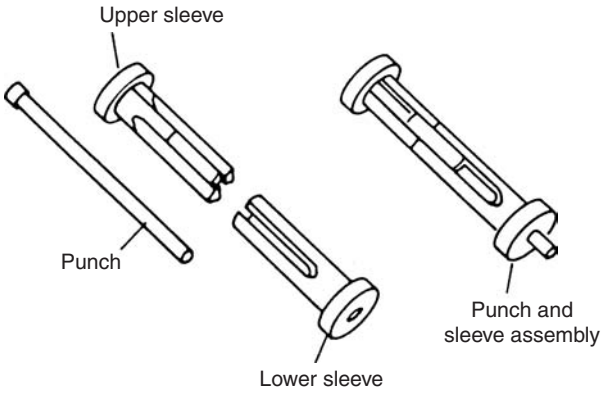

FIGURE 6-37 Guided punch assembly (Durable Punch and Die Co.) (*From: O.D. Lascoe*, "Handbook of Fabrication Processes," *published by ASM International. Reprinted with permission from ASM International, Materials Park, OH.*)

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6-9 PRACTICAL ADVICES AND RESTRICTIONS

All kinds of seemingly small details, trivial observations, and minor facts may often alleviate great problems out there in production. Such little notions are included here for the benefit of the reader.

6-9-1 Punching of Small Notches With Larger Punches

Where notches of various shapes have to be produced in a die, designers and toolmakers should never be tempted to take shortcuts. For a V notch, often a square punch is taken; for a half-round, a full-round punch is used (Figs. 6-38 and 6-39).

Such solutions usually create more problems than they solve. To be adequately utilized, where no damage during a prolonged die operation is caused to it, a punch must cut through the material with at least 75 percent of its cutting surface area. Anything less than that will cause it to sway aside, followed by a tendency to buckling, bending, and subsequent breakage.

For that reason, all special shapes should either utilize special-shaped tooling or be performed in a sequence that provides for the utilization of at least three-quarters of their cutting area.

6-9-2 Long and Narrow Tooling

Using long and narrow tooling along the edge of a strip should be avoided wherever possible. Such punches, even though often cutting with a major percentage of their total punch area, will tend to be negatively affected by this operation, especially if the center of their shanks is off the sheet. An alteration of die design, with a larger distance between the edge of the cut and that of the sheet, should be chosen as shown in Fig. 6-40.

The long and narrow punch is always more secure if the whole surface of the tool is used for cutting.

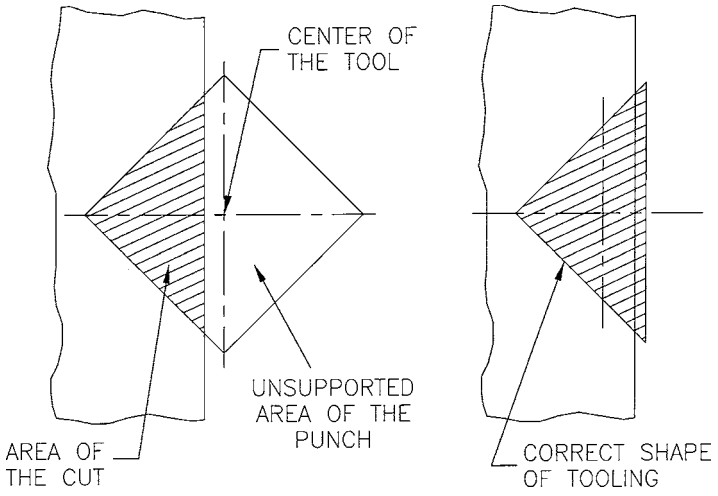

FIGURE 6-38 90° notching of an edge.

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BLANKING AND PIERCING OPERATIONS

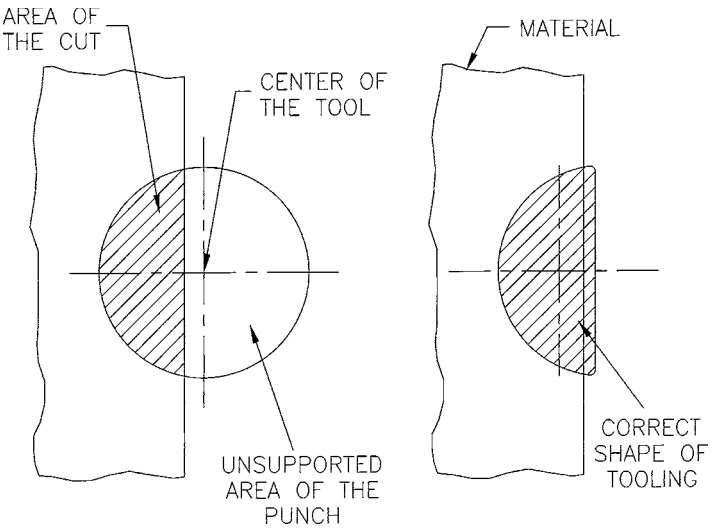

FIGURE 6-39 Half-round notching of an edge.

6-9-3 Cutting of Shapes

Where a complex shape is to be produced in the die, with the final cleanup of scrap to be provided at the end, the designer should beware the dangers not only of unsupported cutting but also of inadequate scrap removal.

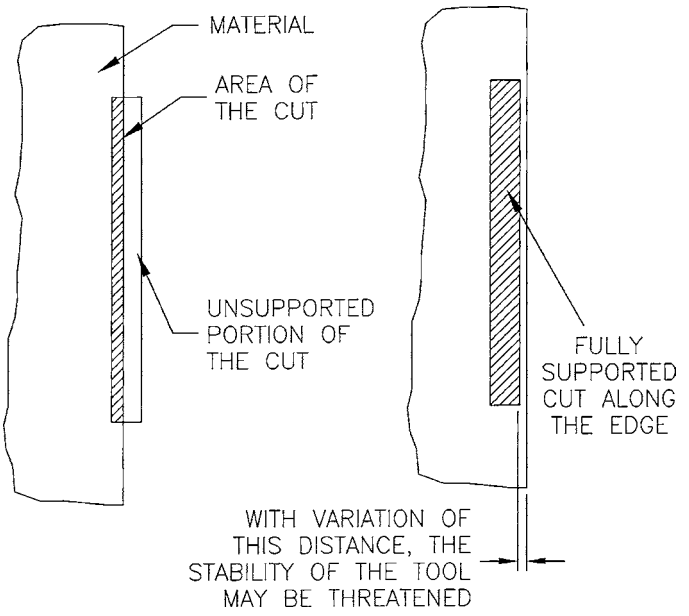
MATERIAL
AREA OF THE CUT
UNSUPPORTED PORTION OF THE CUT
FULLY SUPPORTED CUT ALONG THE EDGE
WITH VARIATION OF THIS DISTANCE, THE STABILITY OF THE TOOL MAY BE THREATENED

FIGURE 6-40 Longitudinal cutting along an edge.

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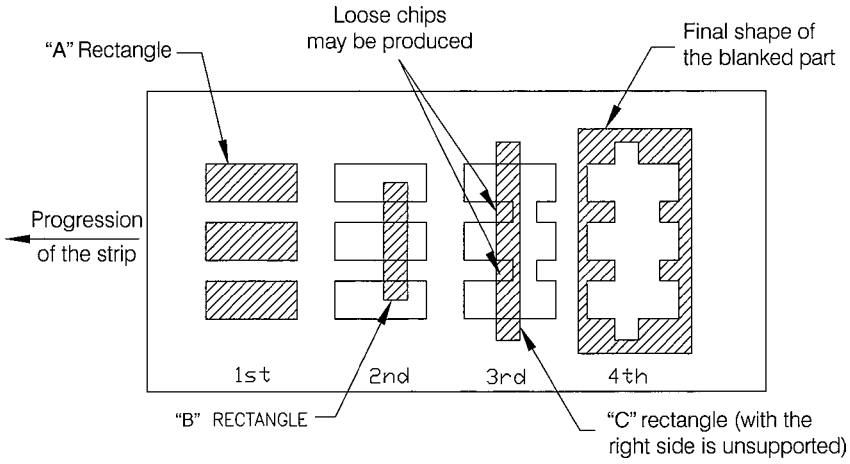

FIGURE 6-41 Supported and unsupported cutting.

In Fig. 6-41, the three rectangular cuts produced with tool (*A*) provide for the main ribbing of a part in the first station. Moving on, the central section is removed by using a rectangular punch (*B*). The remaining portion is cut off in station 3 by a rectangular tool (*C*). The final blanking is performed in station 4.

The cut provided in die section 2 will certainly remove the material, with the load on the punch evenly distributed and therefore acceptable. On the sheet's arrival in the next station, however, with a portion of wall between horizontal ribs already removed, the remainder of that section, only partially attached to the sheet, may be sticking out either way with dependence on the type of material and stripping arrangement. Also, such small sections will certainly not provide the needed support to the long punch (*C*), which will be cutting with its left edge only.

The material removed in station 3 may further complicate the die operation, should some loose chips fail to leave through the opening in the die, as may sometimes happen. These small pieces may remain scattered over the die surface, and threaten its function, endangering the quality of parts. Another possibility of loose chips lying around the die surface, such as those created by piercing of 45° notches with improper tooling, has to be observed (Fig. 6-42). These chips of scrap may obstruct the work of a die by impairing its function or by attacking the surface of a part or of the die.

6-9-4 Cutting of Plastic

Plastics, laminated materials, phenolics, and rubber can all be punched, blanked, or sheared in a die. Naturally, the rules for such production are slightly different from those for cutting of sheet-metal pieces.

The clearance between the punch and die should be an absolute minimum, especially when punching cold material: 1 to 2 percent per side for each 0.031 in. (0.79 mm) of material thickness will suffice. With some plastics, a slip fit between the punch and die may be needed.

The clearance between the punch and the stripper should be kept at an absolute minimum as well.

Some plastics or laminates may be punched cold; some need to be heated. It is advisable to check with the manufacturer for the particular material's preference.

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BLANKING AND PIERCING OPERATIONS

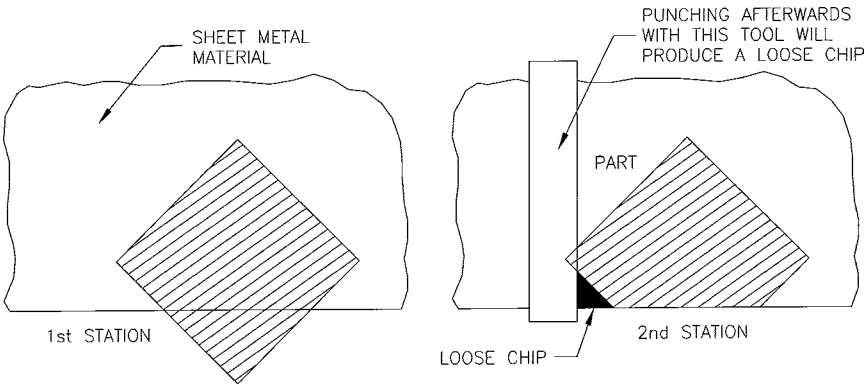

FIGURE 6-42 Chips within the die.

The punch may often need to be made slightly smaller than the required size of the hole, as the opening often closes up on its retrieval. Approximately 0.001 in. (0.03 mm) per diameter reduction in punch size is advisable.

Where rough edges of the punched opening are obtained, a shaving operation may be needed. Sometimes an alternative material-removing method should be chosen to alleviate such a problem.

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CHAPTER 7
BLANK CALCULATION OR FLAT LAYOUT

7-1 THE IMPORTANCE OF FLAT LAYOUT OR BLANK LAYOUT

The importance of an accurate flat layout has been stressed throughout the preceding text. In die work and any sheet-metal work in general, the importance of an accurate and dimensionally correct flat layout cannot be overemphasized. Many problems may be avoided if a full-sized or scaled layout is made first and the part's manufacture is evaluated on the basis of it, instead of referring to the bent-up drawing, which, after all, may or may not be manufacturable.

7-1-1 Flat Layout Development and Calculation

When making a flat layout of a complex part, it always helps to start from a certain side, one that seems to be basic or the most complex, and unfold the remaining portions bend after bend.

A bracket, shown in Fig. 7-1, is simple enough to serve as an example of the unfolding technique. First, the *A* flange may be flattened out to become flush with the vertical portion. This should be done visually, just by looking at the illustration and imagining the flange rotating around its pivoting point or an axis of rotation, as if retained by hinges. Such axis of rotation is always located in the center of bend radius.

Next, the whole vertical segment should be folded down, to become a flat continuation of the horizontal section, as shown in Fig. 7-2. Such a flattened portion may be sketched, adding other segments to it as they are unfolded. To provide the flat layout with dimensions, we start off a single corner and do all dimensioning with regard to that location (for a dimensioned drawing, see Fig. 7-3). However, when checking the numbers later we should calculate them off another location and see if the results will be the same. A sample of flat layout for the bracket is included in Fig. 7-4.

When calculating the dimensions in flat, flange *A* may be assessed off the top of the vertical section (see Fig. 7-3) by subtracting its height from the overall dimension, or

$$3.875 - 2.25 = 1.625 \text{ in.}$$

$$[98.43 - 57.15 = 41.28 \text{ mm}]$$

This dimension is included in Fig. 7-3 as a reference, added for flat layout purpose only. On an actual drawing such a dimension will not be appropriate, as it is already expressed by the difference between 3.875 and 2.25 in [98.43 and 57.15 mm].

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BLANK CALCULATION OR FLAT LAYOUT

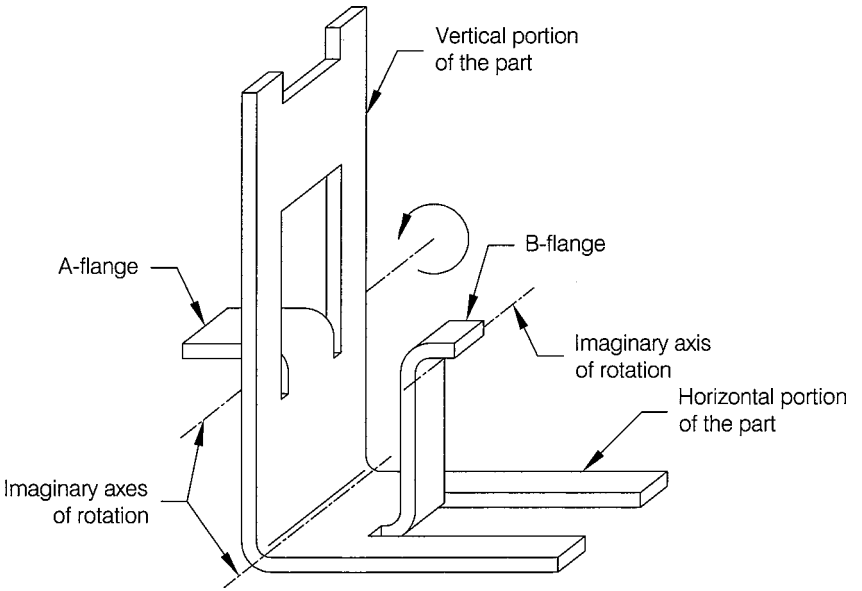

FIGURE 7-1 Sample bracket.

Since the depth of relief slots is not indicated, it is probably not overly relevant, and in such a case we can make these cuts as deep as necessary. Usually, a depth equivalent to the distance measured off the outside surface to the center of the bend radius plus one material thickness, with up to 2*t* will suffice as shown in Fig. 7-5.

The width of the relief slot is not specified either, which similarly allows for a variation. Usually a size of at least one material thickness may suffice, preferably with 1.5*t* to 2*t*.

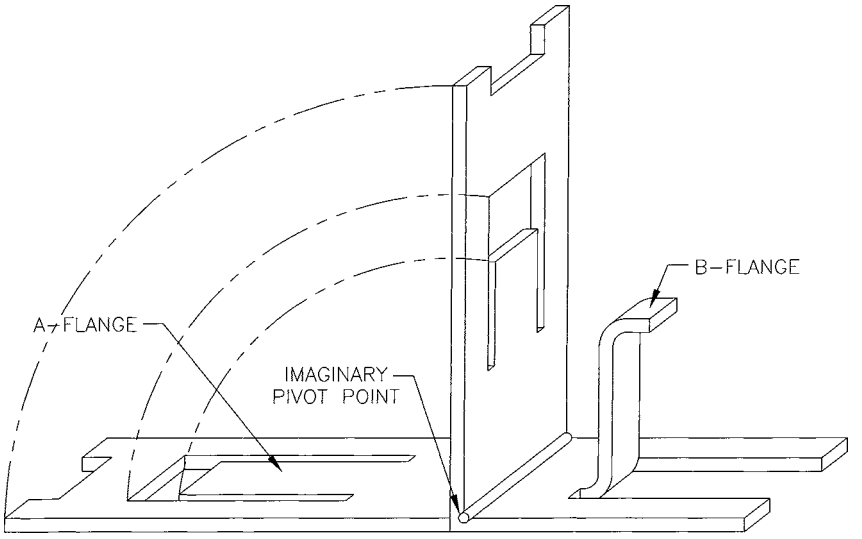

FIGURE 7-2 Flat layout preparation.

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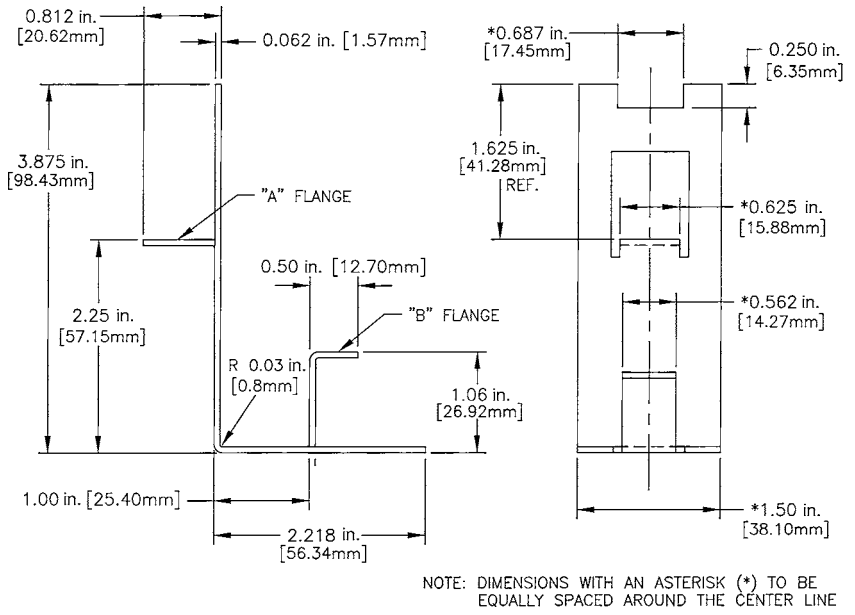
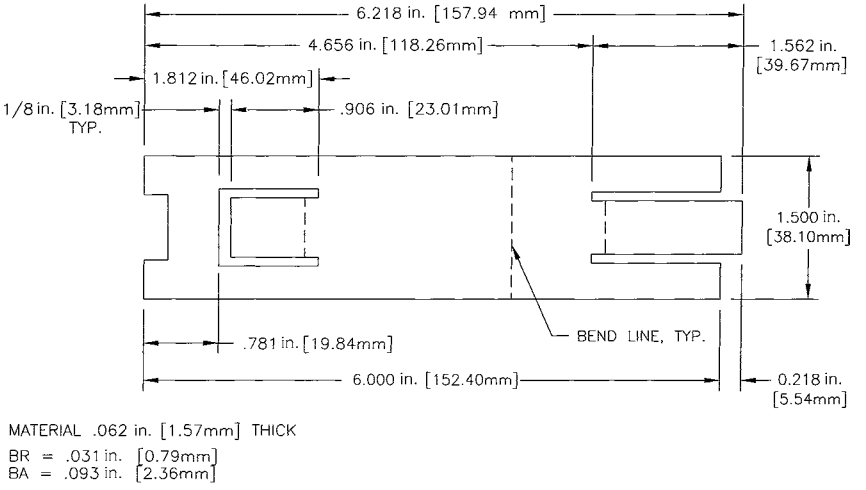


FIGURE 7-3 Bent-up bracket, with dimensions.



MATERIAL .062 in. [1.57mm] THICK
BR = .031 in. [0.79mm]
BA = .093 in. [2.36mm]

FIGURE 7-4 Bracket, flat layout.

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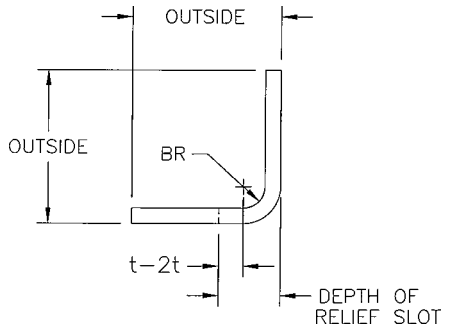

FIGURE 7-5 Bend allowance determination.

The depth of the relief slot's bottom must therefore be calculated by using the dimension

$$1.625 + \text{OuterRad} + 1.5t = 1.625 + 0.093 + 0.093 = 1.812 \text{ in.}$$
$$[41.28 + \text{OuterRad} + 1.5t = 41.28 + 2.36 + 2.36 = 46.00 \text{ mm}]$$

The length of the flange can be calculated by adding the depth of the relief slot measured off the top of the flange (= 0.187 in. or 4.75 mm) plus the length of the flange (= 0.812 in. or 20.62 mm) and subtracting one bend allowance, or

$$0.187 + 0.812 - 0.093 = 0.906 \text{ in.}$$
$$[4.75 + 20.62 - 2.36 = 23.01 \text{ mm}]$$

Bend allowance may be taken off the charts in Chap. 8. Table 7-1 is an additional bend allowance chart, widely used in sheet-metal fabrication, where press-brake bending using V-dies is prevalent. The chart is added to permit a wider range of comparison of dimensions in flat, which sometimes are advisable to calculate using several different techniques.

To use this chart, outside dimensions of each bend must be added up, with one bend allowance per bend subtracted from the total. Where the material thickness or bend radius are not included, such information may be calculated by using the formula

$$BA = 2t - \left[\frac{\pi}{2}(0.45t + BR) - 2BR\right] \tag{7-1}$$

For a so-called sharp bend, the formula will become

$$BA = 1.5t - \left[\frac{\pi}{2}(0.50t + BR) - 2BR\right] \tag{7-2}$$

where BA = bend allowance
BR = bend radius
t = material thickness
$0.45t$ = 45 percent shrink allowance for a radiused bend
$0.50t$ = 50 percent shrink allowance for a sharp bend

Continuing with the evaluation of a flat layout shown in Fig. 7-4, some dimensions may be found to double each other by expressing the same information calculated off two different ends of the part. It sometimes pays to include these on the flat layout, especially

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TABLE 7-1 Bend Allowance Chart for Sheet-Metal Material, V-Die Bending*

Material thickness	Bend radius																
	0.015	0.031	0.062	0.093	0.125	0.156	0.187	0.218	0.250	0.281	0.312	0.343	0.375	0.406	0.437	0.468	0.500
Inches																	
0.015	0.026	0.033	0.046	0.059	0.073	0.086	0.100	0.113	0.127	0.140	0.153	0.167	0.180	0.194	0.207	0.220	0.234
0.018	0.030	0.037	0.050	0.063	0.077	0.090	0.104	0.117	0.131	0.144	0.157	0.170	0.184	0.198	0.211	0.224	0.238
0.024	0.037	0.044	0.058	0.071	0.085	0.098	0.111	0.125	0.138	0.152	0.165	0.178	0.192	0.205	0.219	0.232	0.246
0.031	0.047	0.053	0.067	0.080	0.094	0.107	0.120	0.134	0.147	0.161	0.174	0.187	0.201	0.214	0.228	0.241	0.255
0.036	0.053	0.060	0.073	0.086	0.100	0.114	0.127	0.140	0.154	0.167	0.180	0.194	0.208	0.221	0.234	0.247	0.261
0.047	0.067	0.074	0.087	0.101	0.114	0.128	0.141	0.154	0.168	0.181	0.195	0.208	0.222	0.235	0.248	0.262	0.275
0.054	0.076	0.083	0.096	0.110	0.123	0.137	0.150	0.163	0.177	0.190	0.204	0.217	0.231	0.244	0.257	0.271	0.284
0.062	0.087	0.093	0.107	0.120	0.134	0.147	0.160	0.174	0.187	0.201	0.214	0.227	0.241	0.254	0.268	0.281	0.295
0.078	0.107	0.114	0.127	0.141	0.155	0.168	0.181	0.194	0.208	0.221	0.235	0.248	0.262	0.275	0.288	0.302	0.315
0.093	0.127	0.134	0.147	0.160	0.174	0.187	0.201	0.214	0.228	0.241	0.254	0.267	0.281	0.295	0.308	0.321	0.335
0.109	0.147	0.154	0.168	0.181	0.195	0.208	0.221	0.235	0.248	0.262	0.275	0.288	0.302	0.315	0.329	0.342	0.356
0.125	0.168	0.175	0.188	0.202	0.215	0.229	0.242	0.255	0.269	0.282	0.296	0.309	0.323	0.336	0.349	0.363	0.376
0.140	0.187	0.194	0.208	0.221	0.235	0.248	0.261	0.275	0.288	0.302	0.315	0.328	0.342	0.355	0.369	0.382	0.396
0.156	0.208	0.215	0.228	0.242	0.255	0.269	0.282	0.295	0.309	0.322	0.336	0.349	0.363	0.376	0.389	0.403	0.416
0.171	0.228	0.234	0.248	0.261	0.275	0.288	0.301	0.315	0.328	0.342	0.355	0.368	0.382	0.395	0.409	0.422	0.436
0.187	0.248	0.255	0.268	0.282	0.295	0.309	0.322	0.335	0.349	0.362	0.376	0.389	0.403	0.416	0.429	0.443	0.456
0.203	0.269	0.276	0.289	0.302	0.316	0.329	0.343	0.356	0.370	0.383	0.396	0.410	0.423	0.437	0.450	0.463	0.477
0.218	0.288	0.295	0.309	0.322	0.336	0.349	0.362	0.375	0.389	0.403	0.416	0.429	0.443	0.456	0.469	0.483	0.497
0.234	0.309	0.316	0.329	0.343	0.356	0.370	0.383	0.396	0.410	0.423	0.437	0.450	0.464	0.477	0.490	0.503	0.517
0.250	0.330	0.337	0.350	0.363	0.377	0.390	0.404	0.417	0.431	0.444	0.457	0.471	0.484	0.498	0.511	0.524	0.538

(*Continued*)

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TABLE 7-1 Bend Allowance Chart for Sheet-Metal Material, V-Die Bending* (*Continued*)

Material thickness	Bend radius																
	0.50	0.75	1.50	2.50	3.50	4.00	4.75	5.50	6.25	7.00	8.00	8.75	9.50	10.25	11.00	12.00	13.00
Millimeters																	
0.40	0.73	0.84	1.16	1.59	2.02	2.23	2.56	2.88	3.20	3.52	3.95	4.27	4.59	4.92	5.24	5.67	6.10
0.50	0.86	0.97	1.29	1.72	2.15	2.36	2.69	3.01	3.33	3.65	4.08	4.40	4.72	5.05	5.37	5.80	6.23
0.63	1.03	1.14	1.46	1.89	2.32	2.53	2.85	3.18	3.50	3.82	4.25	4.57	4.89	5.21	5.54	5.97	6.39
0.80	1.25	1.36	1.68	2.11	2.54	2.75	3.07	3.40	3.72	4.04	4.47	4.79	5.11	5.43	5.76	6.18	6.61
1.00	1.51	1.62	1.94	2.37	2.80	3.01	3.33	3.65	3.98	4.30	4.73	5.05	5.37	5.69	6.01	6.44	6.87
1.20	1.77	1.87	2.20	2.62	3.05	3.27	3.59	3.91	4.23	4.56	4.99	5.31	5.63	5.95	6.27	6.70	7.13
1.40	2.03	2.13	2.45	2.88	3.31	3.53	3.85	4.17	4.49	4.81	5.24	5.57	5.89	6.21	6.53	6.96	7.39
1.60	2.28	2.39	2.71	3.14	3.57	3.79	4.11	4.43	4.75	5.07	5.50	5.82	6.15	6.47	6.79	7.22	7.65
2.00	2.80	2.91	3.23	3.66	4.09	4.30	4.63	4.95	5.27	5.59	6.02	6.34	6.66	6.99	7.31	7.74	8.17
2.20	3.06	3.17	3.49	3.92	4.35	4.56	4.88	5.21	5.53	5.85	6.28	6.60	6.92	7.24	7.57	8.00	8.42
2.80	3.84	3.94	4.26	4.69	5.12	5.34	5.66	5.98	6.30	6.63	7.05	7.38	7.70	8.02	8.34	8.77	9.20
3.00	4.09	4.20	4.52	4.95	5.38	5.60	5.92	6.24	6.56	6.88	7.31	7.63	7.96	8.28	8.60	9.03	9.46
3.50	4.74	4.85	5.17	5.60	6.03	6.24	6.56	6.89	7.21	7.53	7.96	8.28	8.60	8.93	9.25	9.68	10.11
4.00	5.39	5.49	5.82	6.25	6.67	6.89	7.21	7.53	7.86	8.18	8.61	8.93	9.25	9.57	9.89	10.32	10.75
4.50	6.03	6.14	6.46	6.89	7.32	7.54	7.86	8.18	8.50	8.82	9.25	9.57	9.90	10.22	10.54	10.97	11.40
5.00	6.68	6.79	7.11	7.54	7.97	8.18	8.50	8.83	9.15	9.47	9.90	10.22	10.54	10.87	11.19	11.62	12.05
5.50	7.33	7.43	7.76	8.19	8.61	8.83	9.15	9.47	9.79	10.12	10.55	10.87	11.19	11.51	11.83	12.26	12.69
6.00	7.97	8.08	8.40	8.83	9.26	9.48	9.80	10.12	10.44	10.76	11.19	11.51	11.84	12.16	12.48	12.91	13.34
7.00	9.27	9.37	9.70	10.13	10.55	10.77	11.09	11.41	11.73	12.06	12.49	12.81	13.13	13.45	13.77	14.20	14.63

*Use the outside dimensions of each bend and subtract the bend allowance shown.

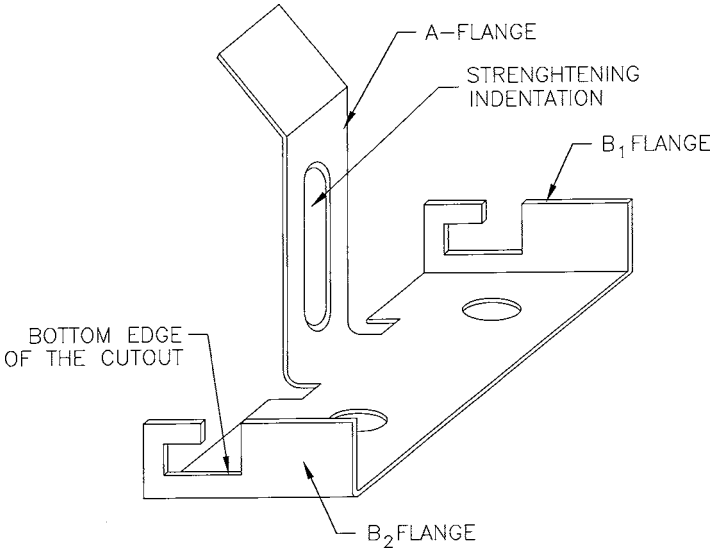

FIGURE 7-6 Support bracket, bent-up part.

where certain locations will have to be constantly recalculated off different ends. These dimensions may also serve as an efficient way of checking the flat layout, especially where the same person who drew and calculated it will have to check it and manufacture the part.

The flat length of the flange *B* should be calculated the same way as described previously. Here, the difference between the outer edge of the horizontal portion and that of the flange should be figured starting off the bottom of the relief slot, which should be established first. To verify the calculation, dimensions off the left edge of the blank should be used.

The bracket, shown in Fig. 7-6 presents a slightly different problem. Here, the flange *A* contains an oval indentation for strengthening. Side flanges B_1 and B_2 show sharp-cornered cutouts of considerable size, which may cause problems in bending, because their bottom edge is located only 1.5*t* off the center of bend radius. The dimensioned bent-up drawing of the part and its flat layout are included for study and comparison of results (see Figs. 7-7 and 7-8).

7-1-2 Phantom Areas

A part in Fig. 7-9 containing so-called *phantom areas* is shown for evaluation. Phantom areas are portions of unavailable material, not obvious from the bent-up drawing (see Fig. 7-10). Only on observation of the flat layout (shown in Fig. 7-11), it becomes clear that it will be impossible to obtain the shaded corners of the two side flanges from the material given.

A change of either part's manufacturing process or that of its outline will have to be made. If the outline must be kept, the manufacturing process can have the two corners welded on later and sanded smooth—an operation quite expensive, unpractical, and cumbersome. Some may volunteer to weld both sides to the flat bottom, which will totally defeat the practicability of die-manufacturing process.

A folded-up drawing of the part with dimensions and its flat layout are included for personal comparison and study. Note the width of the bottom flat portion being made 0.81 + 0.00/–0.01 in [20.6 + 0.0/–0.2 mm] on the flat layout, in congruence with the folded-up drawing shown in Fig. 7-10, where a material-thickness wide gap is shown between

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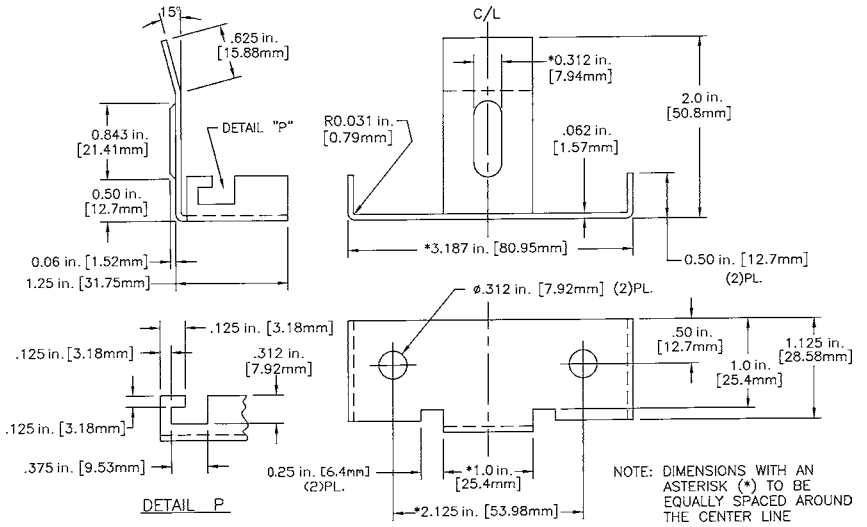

FIGURE 7-7 Support bracket. Bent-up part with dimensions.

the bottom and inner walls of the enclosure. The tolerance range in this case depends on several variables, such as

- Material thickness and its tolerance, especially the increase in thickness
- Tolerance requirements for the 1.0 in. [25 mm] overall width of the part, as shown in Fig. 7-10.

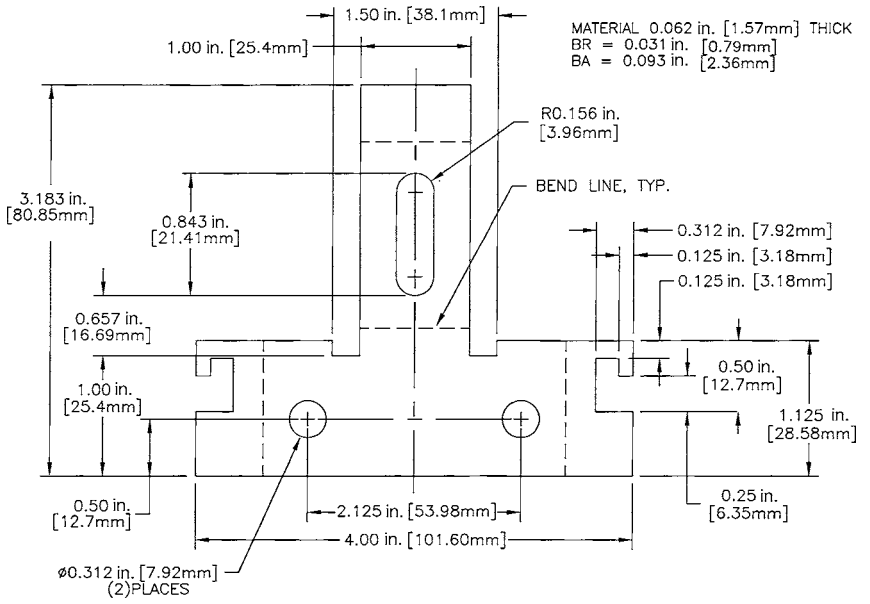

FIGURE 7-8 Support bracket, flat layout.

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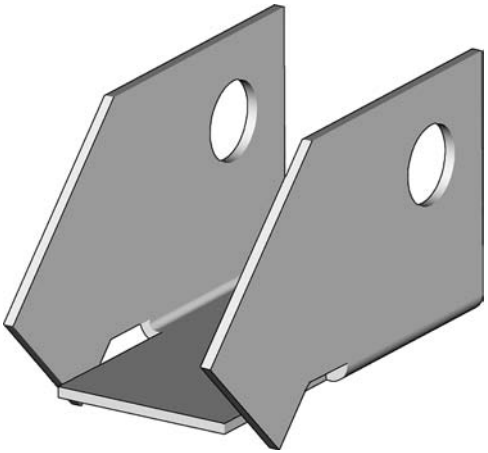

FIGURE 7-9 Cover, bent-up part.

- The size of permissible gap between the edge of the flat bottom material and the inner surface of the two side flanges
- Bending operation tolerance range

If changes to the part's outline were permissible, these are included in Fig. 7-12. In the first illustration, the sharp corners previously interfering with the middle section of the part were removed and the relief slot was brought all the way through, on each side. The second picture shows the sharp corners respected with the middle section narrowed down to allow for their procurement.

The design shown in Fig. 7-13 considers the sharp corners as being used for offsetting the part off a certain surface. Yet, these corners were removed and their function taken over by the middle shelf, bent down to provide the offset in the location where needed. If shortening

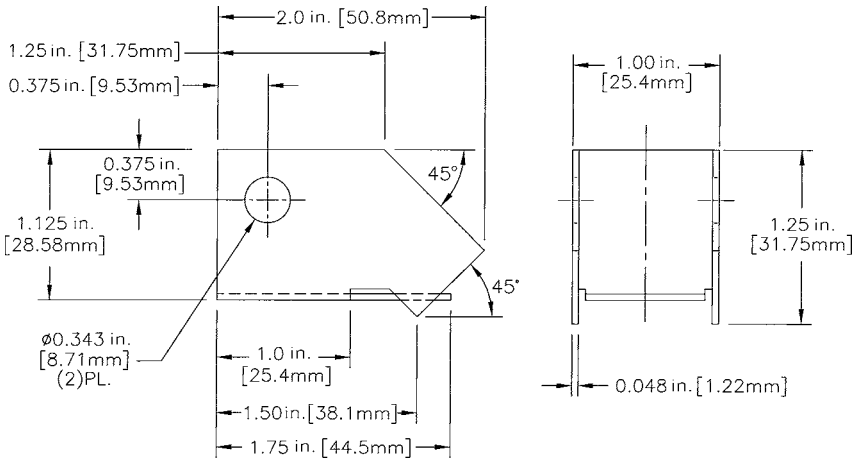

FIGURE 7-10 Cover, bent-up part with dimensions.

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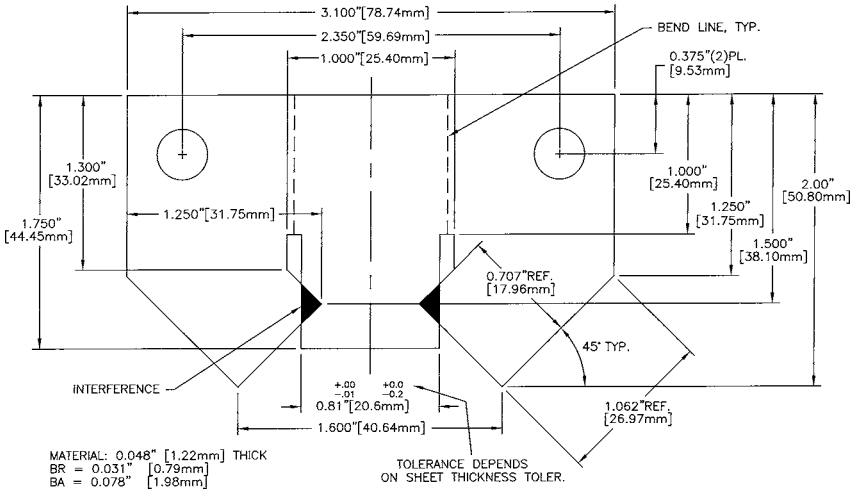

FIGURE 7-11 Cover, flat layout.

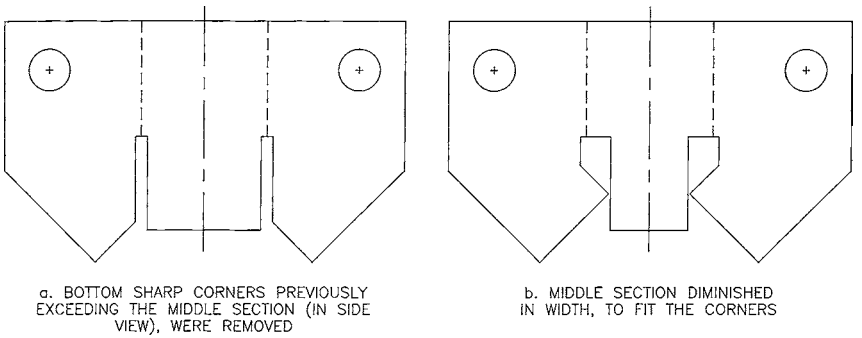
a. BOTTOM SHARP CORNERS PREVIOUSLY EXCEEDING THE MIDDLE SECTION (IN SIDE VIEW), WERE REMOVED
b. MIDDLE SECTION DIMINISHED IN WIDTH, TO FIT THE CORNERS

FIGURE 7-12 Cover, change of design.

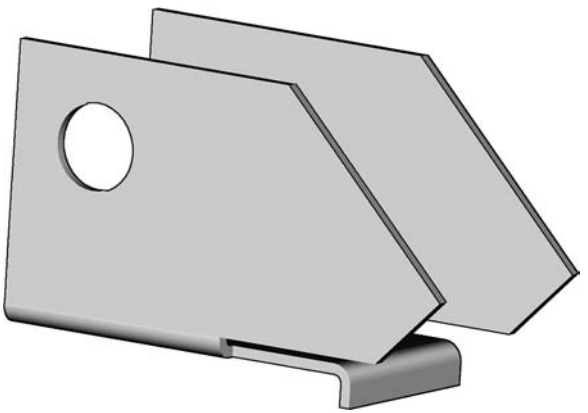

FIGURE 7-13 Cover, another design change.

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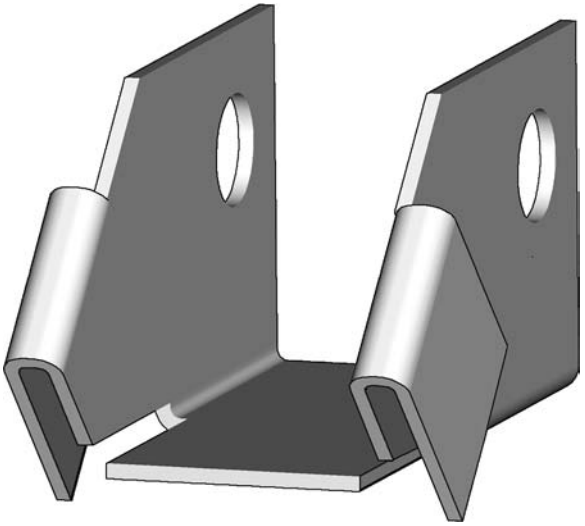

FIGURE 7-14 Cover, redesigned part.

of the middle surface be objectionable, tabs on each side of the flat bottom can be produced, while the center can be kept at the length needed.

The final idea, presented in Fig. 7-14, makes the sharp corners from the bent-up sides of each flange. Such a U-bend, called a *Dutch bend*, can be flattened in the die, which will press both the surfaces together. This way the so much sought-after sharp corners will be there, but a material thickness away. The flat layout of this design is presented in Fig. 7-15.

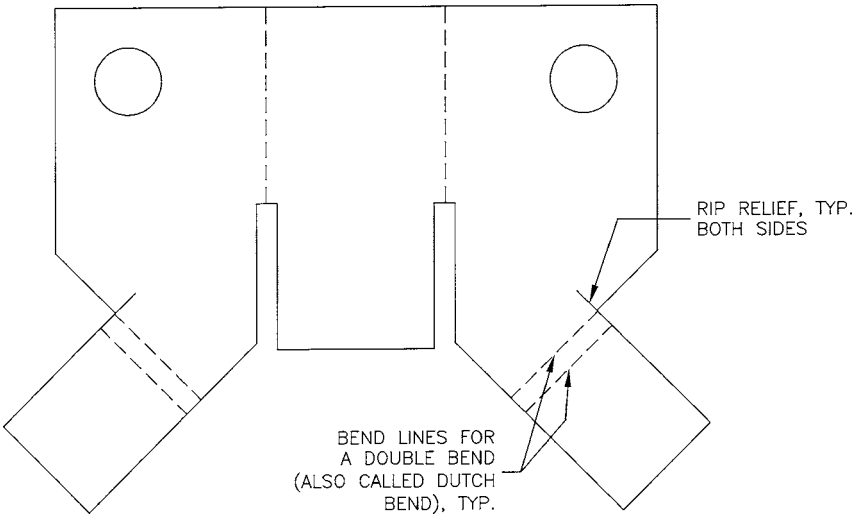

FIGURE 7-15 Cover, flat layout of redesigned part shown in Fig. 7-14.

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7-1-2-1 Offset Bracket Sample. Another phantom area-containing bracket is shown in Fig. 7-16. Here, the two prongs are located on the same bend line, while the middle prong is offset backward.

The middle offset prong has two side flanges, each pierced at two places. These flanges, when observed on the flat layout shown in Fig. 7-17, cannot actually be made, as there is not enough material for their width.

If these flanges were located higher up, plenty of stock will be available once their location exceeds the top edge of the two side prongs. However, let us assume their location is firm and must remain as such.

There seems to be no chance of producing the material for these flanges from anywhere unless it is taken from the material of the two prongs, as shown in Fig. 7-18*A*. Provided the sharp-edged cutout and the difference in width of the prongs' top will not impair the overall function of the part, this may become a solution to a given problem. Where the sharp edge may be objectionable, it may be either rounded or chamfered, as shown by dotted lines.

Tooling for such a design change will be more costly, for which reason an overall widening of the relief slot, shown in Fig. 7-18*B*, may be more advantageous.

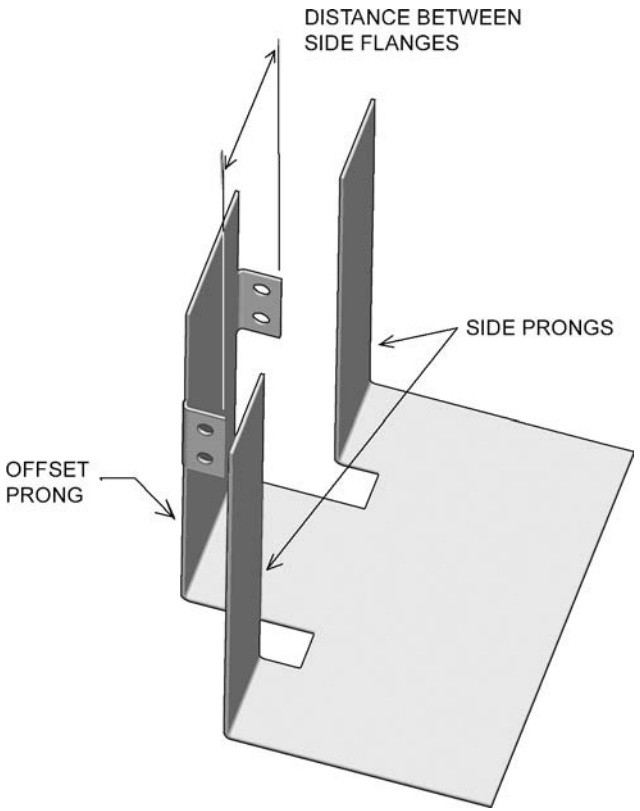

FIGURE 7-16 Offset bracket, bent-up part.

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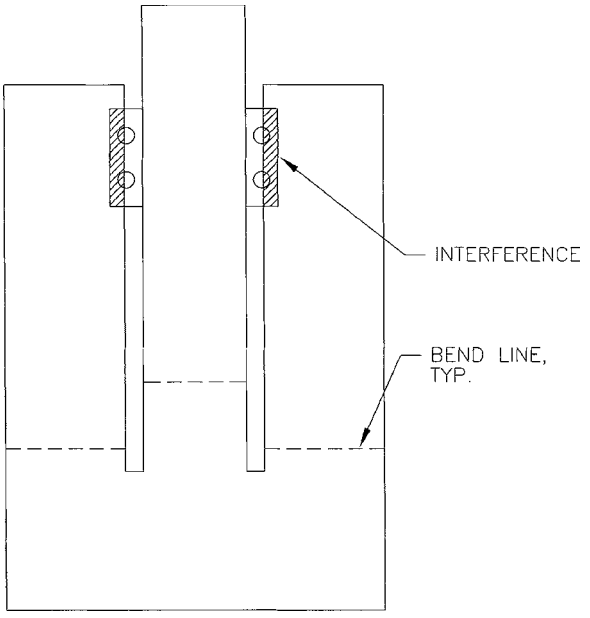

FIGURE 7-17 Offset bracket, flat layout.

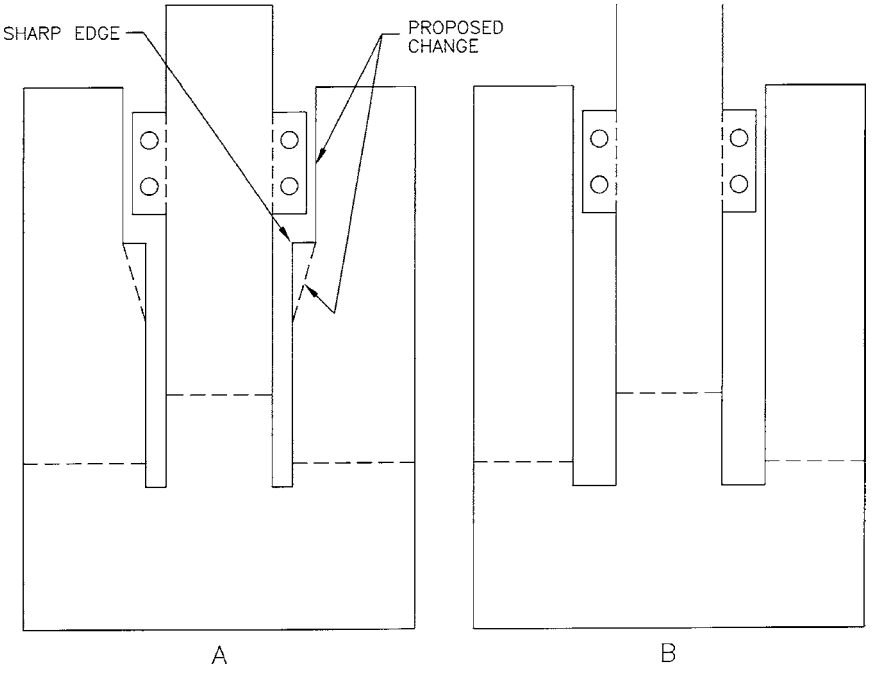

FIGURE 7-18 Offset bracket, flat layout variation no. 1.

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Naturally even this solution may not suffice, and another alternative has to be sought after. Shown in Fig. 7-19 is a different method of changing the given design. Here, the top of the middle prong is extended farther and spread out sideways, the extension being equal to the offset of two small side flanges, as shown in the folded view.

Such a change may seem to do the job of placing the two-side flanges in an appropriate location, but at a very steep price, for the part is much higher now with its width increased as well. Aside from the obvious wastage of material, an additional two bending operations are included. Also a possible need for two small tabs *P* may arise, if the two narrow strips-turned-flanges are to be secured to the body of the middle prong. Such a design is not only impractical, it is outright clumsy.

In Fig. 7-20 is shown yet another attempt at design change of the given flat layout, where the relief cuts of the two side prongs have been slanted. It is perhaps a slightly less practical variation of the Fig. 7-18*A* and *B* method. The tool, cutting the angled portion, may not be narrow enough to miss the corner of each side flange, which may result in an involuntary and also uneven chamfer of its edge.

The size of the tool should concern us here, as such a large punch may require skipping an extra station in the progressive die. The other side may need an additional station to skip, and the final size of the die may be enormous.

Figure 7-20*B* depicts a halfway method, where the material for side flanges is taken off the area between the prongs by sinking the flanges into the material of the middle prong. This solution can be used where the horizontal distance between the flanges, as shown in Fig. 7-16, can be changed without impairing the function of the part.

The final design change is shown in Fig. 7-21. The compromise presented here involves a slight narrowing of the side prongs, with a slight narrowing of the two

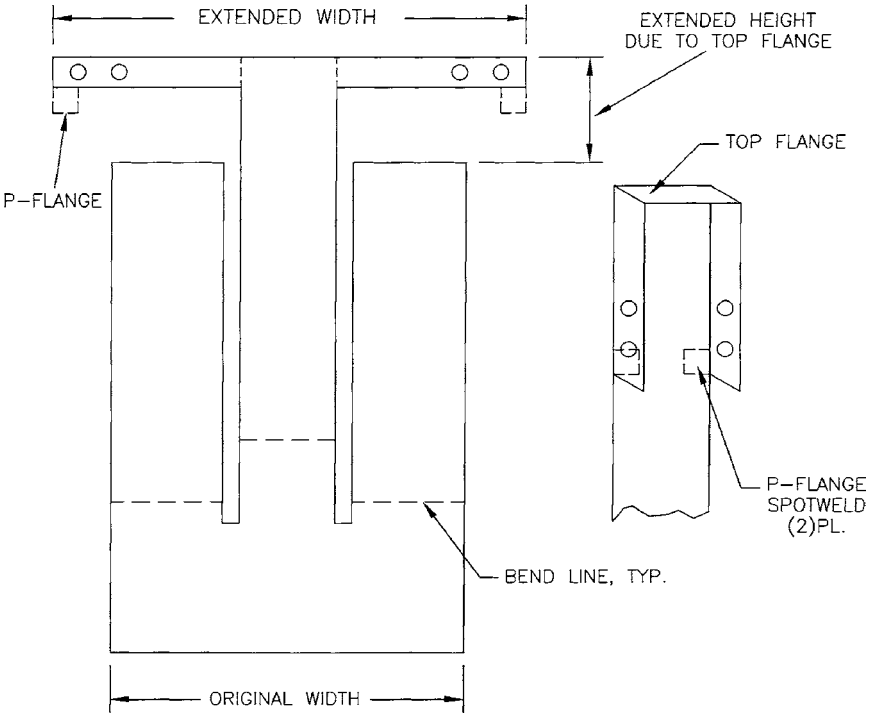

FIGURE 7-19 Offset bracket, flat layout variation no. 2.

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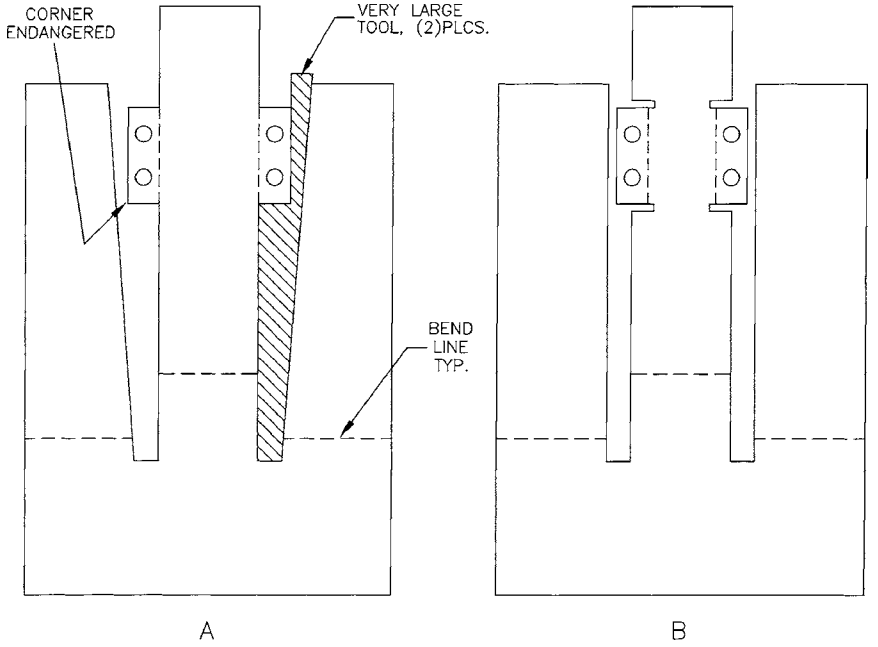

FIGURE 7-20 Offset bracket, flat layout variation no. 3.

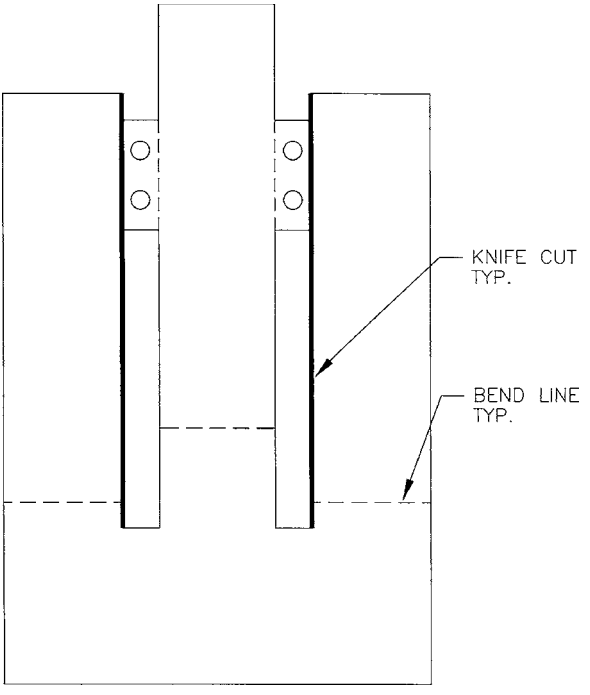

FIGURE 7-21 Final design change.

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flanges as well. This will leave enough gap in between for the material of the two side flanges.

We will need to clean up the area of each gap after producing a knife cut along the prongs' edges. This cut will totally separate each flange from its side prong, producing a continuous edge with no tool marks or steps. The prongs may be bent down somewhat by its action, which can be repaired by pushing them back with a pressure pad.

7-2 DETAILS OF A FLAT LAYOUT

When making a flat layout, there are certain areas where paying attention to the detail saves a great many headaches later, when the tooling is made in steel. These areas of interest are mainly corner-relief slots, transitions between radii and straight surface lines, holes and their location off bends, and the like. Many of these problem-prone areas may be successfully produced by a simple adjustment of the manufacturing sequence of operations, but there are cases where such a solution would not be adequate.

Naturally, the importance of the positioning of parts with regard to the material grain is vital to the functionability of the product and to its manufacturability as well. Further, a correct assessment of the part's burr side and design of tooling in accordance with its location is of essence.

For example, to place a switch cover with the burr side up may tear the skin of the user, provided the switch is embedded within the cover plate. A similar effect would be achieved by reversing the burr side of the binder's opening-closing lever mechanism or that of any closure, hardware, and many other items of daily personal and industrial use.

The location of a burr with reference to the functional side of the part may cause the final product to either make it or break it, as they say. Therefore, a careful observation of the part and a correct assessment of its surfaces would be of essence where the location of the burr is not specified on the drawing.

7-2-1 Details of Corners and Relief Slots

In order to eliminate the possibility of sharp corners, some parts have their edges chamfered or rounded. This in itself seems like a logical solution when considering their functionability, but to actually produce such a corner is a different story. It is quite easy to chamfer an edge by using a square tool under 45° angle and hitting each corner prior to blanking its outline. We already know that we should not attempt to perform such a sequence of operations in reverse, and to chamfer the corner after the outline is blanked out, since the punch, cutting with but a small portion of its face total area, will have a tendency to buckling and breakage.

However, rounding of edges of parts is a completely different matter. With large-sized items, which demand a small, perhaps even dimensionally unspecified corner radius, this will not be such a problem. These parts may always be touched up individually later. But with small parts pouring from the die in quantity, a different solution will be needed where rounding of their corners is required.

As seen in Fig. 7-22*A*, a radius tool is used to produce a quarter-circle cut, with the rest of the material being chopped off by a rectangle. No matter which way the sequence of operations is arranged, a step between the cuts may be produced if the tooling is not sharp or tight enough, or where the detrimental qualities of the material, such as high ductility or brittleness, are present.

Where the tools overlap, a step may be produced at either or both ends of the length of the overlap. This may be even more complicated if punching first with the rectangle and

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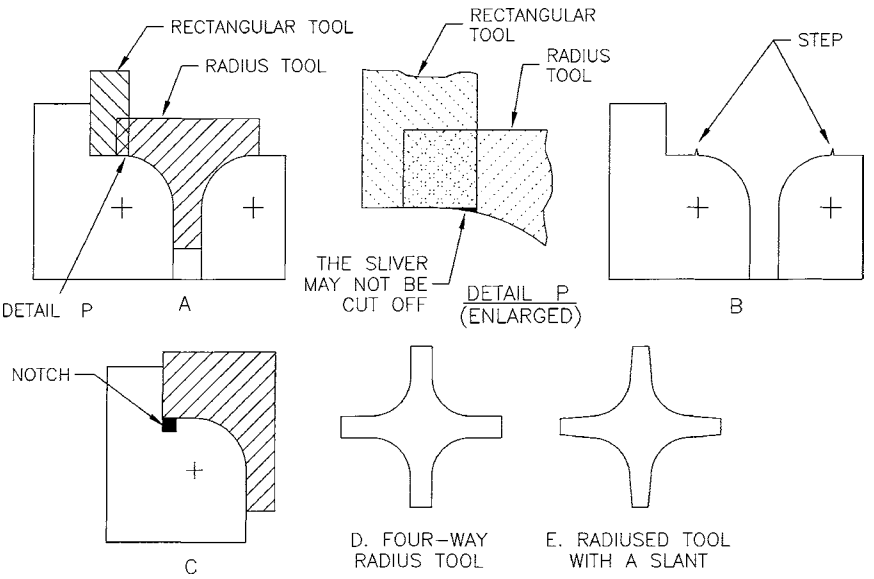

FIGURE 7-22 Corner radii.

following up with the radius tool. A small sliver of material, shown in the enlarged detail *P*, may not be cut off properly. Because of its insignificant size, this little corner may fit within the tooling tolerance range, and instead of being cut off, it will be squeezed down, where it will aid in the formation of the burr.

An alternative to detail *A* cutting is presented in detail *C* of the same illustration. Here the whole area is removed by a single punch, shaped to suit the required size and contour. However, even though the resulting cut will be perfect, a tool like this is highly specialized, usable for one particular cut only. Where the other side of the part will need the same rounding to be produced, another tool—a mirror image of the first one—will have to be made.

A four-way radius tool, often used in sheet-metal practice for procurement of radii at various locations, is shown in Fig. 7-22*D*. We may expect interference and sliver appearance similar to detail *P* description, where the abrupt edge of this tool encounters another cut. Perhaps the cheapest way to avoid this happening is to incline the sides of the four-way radius tool (or any other tool, for that purpose), right after the quarter-circle, as shown in detail *E*. Of course, the rectangular cut must be performed first with the radius tool, but touching up the edge.

Corners of sheet-metal parts may often pose a problem, especially where joining two flanges together, as seen in Fig. 7-23*A*. Here the two edges of a box-type shape must be very close, almost touching. Some may attempt to pattern the relief slots as shown in detail *B*. This solution may often be used with different sizes of bend radii, provided the sharp corner may be removed where it should exceed the shape of the part. A method of replacing such a complicated relief slot pattern with a single round opening, shown in detail *C*, may often be a better solution. The sharp corner will be shifted into another location, with its size and sharpness dependent on the distance of the round tool off the part's edge.

Another manufacturing method of producing a corner relief is to offset both cuts slightly below the bend line, as shown in Fig. 7-23*D*. Such an arrangement will certainly work well

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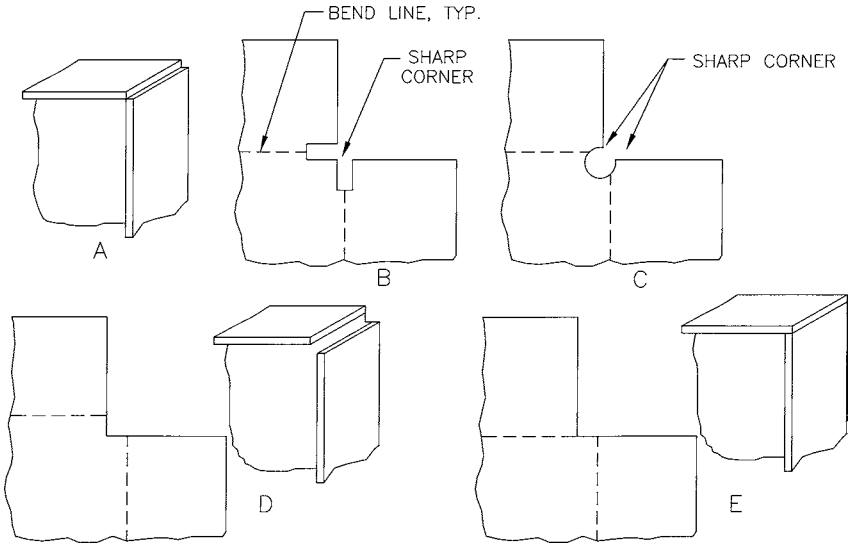

FIGURE 7-23 Corner design variations no. 1.

with parts, where a sharp edge is permissible, and the gap between the two sides can be controlled by the distance of the cutter off the bend line. An alternative of the same joining method is shown in *E*, where one side of the box is bent to fit under the other flange.

Face flanges present a slightly different challenge to the avid die or sheet-metal designer. Here the corner may be finished either by joining two perpendicular flanges or by providing a 45° cut in the middle, as shown in Fig. 7-24*A* and *D*, respectively.

The method of corner finishing depicted in detail *A* will always display a gap of some kind, especially where larger bend radii are involved. With large-sized parts, these gaps may be filled in and ground smooth, but with small, mass-produced items, such a finishing procedure is highly unreasonable. A 45° cut is more appropriate in a case like this.

The amount of space between the adjoining flanges shown in *D* may be diminished to a negligible size by a correct assessment of the depth of relief cut. The variation of such space will be achieved by moving the peak of the cut with reference to the face bend line, as shown in *E* and *F*.

An easy method of evaluating the gap size is to calculate the exact position of the edge of each flange and determine the size of the space between them by using basic trigonometry. Naturally, the bend allowance for such a bend must be divided equally between both sides of a part. Where the peak of a relief cut will end at the bend line, a slight bulging of the material around that area may be expected after bending.

Sometimes, if the closest possible contact between the two flanges is required, some bend reliefs are purposely made smaller than necessary, allowing for tearing of the material in bending. This is done especially with large parts, where these areas may be sanded smooth later on.

7-2-2 Holes Versus Bends

The location of openings with reference to the bend line is of considerable importance in sheet-metal practice. The metal material, when subjected to stretching and compressing during the bending process, has a tendency to extend the shape of a hole, changing its contour

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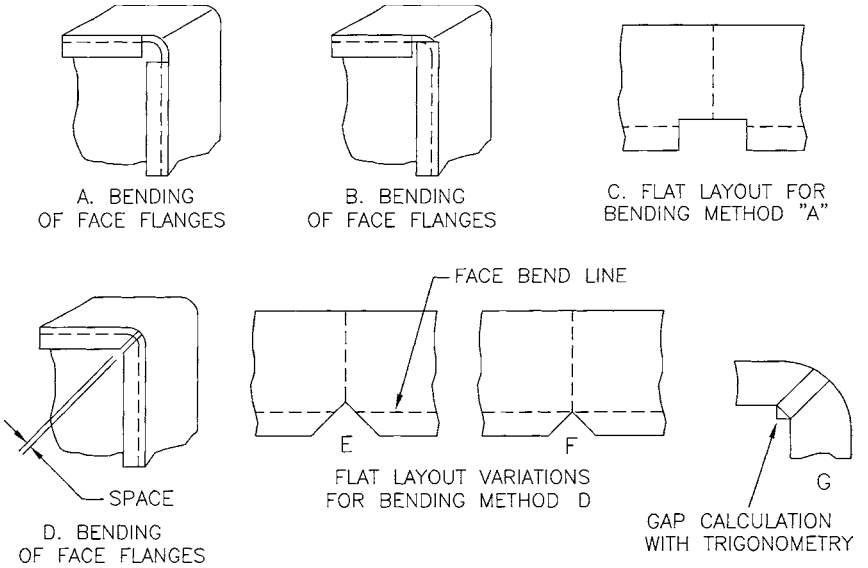

FIGURE 7-24 Corner design variations no. 2.

from round to elliptical. This may be prevented where it is possible to bend the part first and pierce the holes afterward. However, such a work sequence may involve a side action of the die, utilizing cams, which is not always the most desirable method of solving this problem.

In some cases, the holes in question may be pierced oval in shape, so that when being tugged upon by the strain of the bending process, their elongation will actually make them round. See Fig. 7-25.

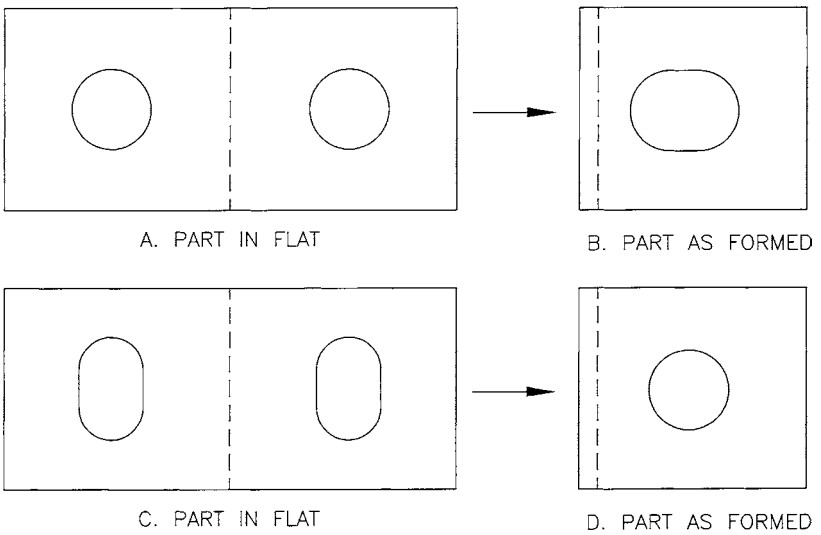

FIGURE 7-25 Shape of openings altered by bending.

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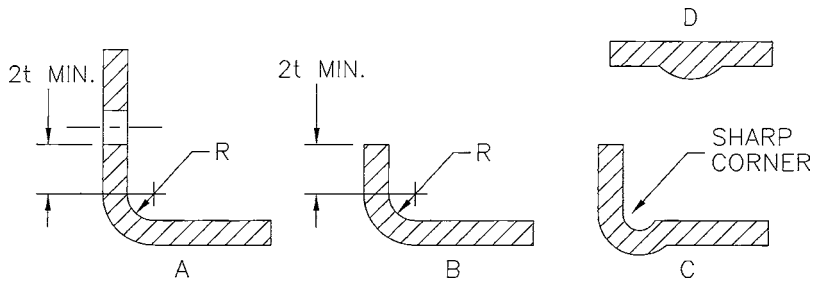

FIGURE 7-26 Location off the bend.

The minimal distance of the edge of an opening off the bend should equal 2*t*, or two material thicknesses, measured off the center of the bend radius. In the same way the edge of the part should be at least two metal thicknesses off the center of the radius, as shown in Fig. 7-26.

Where a sharp corner bend is absolutely necessary, perhaps to serve as a relief for the corner of an adjoining part, it may be produced by restriking the bent-up part with the intention of sharpening the inner radius. Since during such a process the material of the edge will be slightly diminished in thickness, some bulging of the bend line may be needed prior to the bending operation, as shown in Fig. 7-26*D*.

7-2-2-1 Relief Openings. To punch relief openings in metal, such as those providing an access for the assembly tool (see Fig. 7-27), or clearance holes for screws or other inserts, it pays to make these holes as large as possible. Larger openings not only provide for a positive relief action, they are not easily affected by any dimensional discrepancy, which in bent-up parts may sometimes be seen.

Openings where the location of their center with respect to the corresponding part is outright questionable, as with segments of large-sized assemblies or constructions, oval holes should replace rounds, with the longer side of the shape positioned along the path of the expected dimensional discrepancy (see Fig. 7-27*C*).

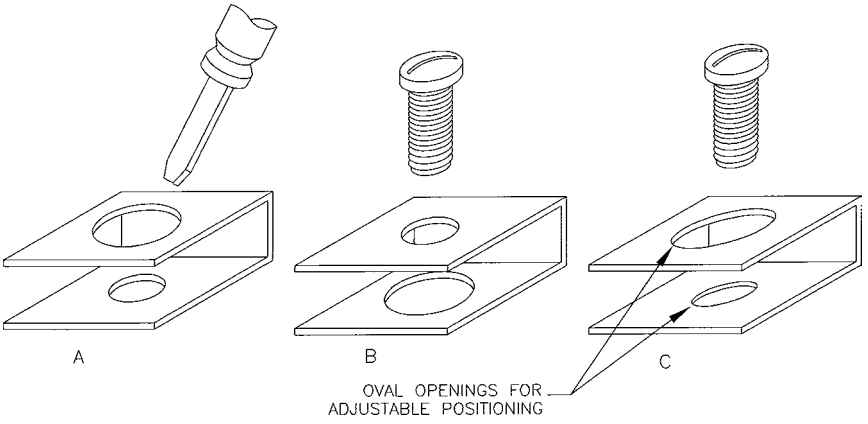

FIGURE 7-27 Access openings.

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7-2-2-2 Extruded Openings and Bosses The size and depth of extruded shapes should be calculated the same way a bend would be assessed. After all, that is what these contours are, when observing their cross-sectional outlines: they are bent-up, sometimes slightly drawn shapes.

Most extruded openings must first be pierced in order to provide enough space for the extruding punch, which is to form the edges afterward. To calculate the size of the basic opening, we must assess the length of the bent-up (or extruded) portion, apply the necessary bend allowance, and subtract the result from the size of the extruded shape, or

$$d = 2[B - (A + h - BA)] \tag{7-3}$$

where *BA* is the bend allowance.

All other values are given in Fig. 7-28.

This calculation does not take into consideration any drawing tendency of the material, figuring the obtained shape to be attributable strictly to bending.

Often such a calculation may be used when determining the largest possible height *h*, obtainable from the smallest possible pierced opening. In such a case, the diametral size of the original opening with respect to the diameter of the final shape (2*B* dia.) are the factors limiting the height of the extruded shape.

Bosses and dimples may be evaluated the same way; however, these indentations often contain some stretching of material with subsequent thinning of some sections.

7-2-3 Dutch Bends and Joggles

Dutch bends, or 180° bends, are used as hems in sheet-metal practice (Fig. 7-29). Such bends are actually doubled 90° bends, with the outer surface of the material forming a whole half circle around the center of the bend. There is almost no bend radius with this type of bending.

To calculate the size of a hemmed part in flat, the chart shown in Table 7-2 should be used. Table 7-3 gives the minimal length of hem *A*.

Joggles are offsets in height, connected by a short piece of angular strip of the same material, as shown in Fig. 7-30. Joggles are used where an offset for another part of the assembly is to be provided or where a greater flatness of the actual contact surface is desired. Joggles may also be used to stiffen the part or to provide for collection of liquids, in which case they take the shape of a shallow cuplike indentation within the flat surface.

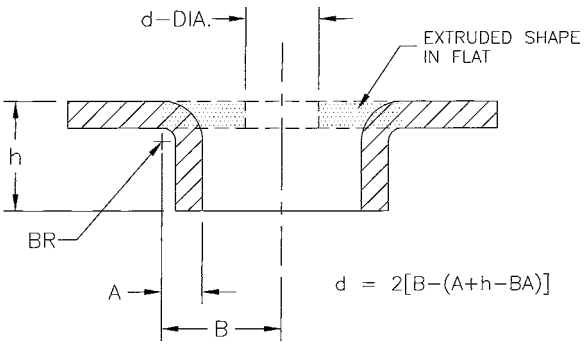

FIGURE 7-28 Extruded openings.

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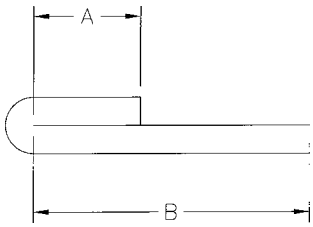

FIGURE 7-29 Dutch bend (hem).

Joggles, indentations, bosses, and other height-altering additions should use the same recommended bend radii as regular bent-up parts. Bend allowances for joggles should be taken in the vicinity of 33 percent of the material thickness. As an example, a 0.060 in. [1.5 mm] high joggle in 0.048 in. [1.25 mm] thick cold-rolled steel will use a +0.014 in. [+0.35 mm] bend allowance.

7-2-4 Interference of Formed Areas

There are occasions when formed sections may interfere with one another. Sometimes this interference is but visual and on creating the flat layout we may see that it actually does not exist. But often the interference may be there, in the formed drawing, and such parts will be quite difficult to make.

As an example, an upper 45° flange in Fig. 7-31 is certainly interfering with the side flange. Where the side flange will be formed first, the upper flange will not have enough space to achieve a slight overbend, needed for the prevention of springback. And where the upper flange will be formed first, it will be in a way when forming the side flange.

TABLE 7-2 Hemming Dimensions in Flat

Material thickness	Total length in flat
Inches	
0.030	A + B + .050
0.036	A + B + .060
0.047	A + B + .080
0.062	A + B + .090
0.093	A + B + .140
0.109	A + B + .160
0.125	A + B + .190
Millimeters	
0.75	A + B + 1.25
1.00	A + B + 1.50
1.25	A + B + 2.00
1.50	A + B + 2.25
2.25	A + B + 3.50
2.75	A + B + 4.00
3.25	A + B + 4.75

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TABLE 7-3 Minimum Length of the Hemming Flange

Material thickness	Minimum "A" dimension
Inches	
0.030	0.250
0.036	0.250
0.047	0.250
0.062	0.250
0.093	0.375
0.109	0.375
0.125	0.375
0.187	0.625
0.250	0.750
Millimeters	
0.75	6.35
1.00	6.35
1.25	6.35
1.50	6.35
2.25	9.50
2.75	9.50
3.25	9.50
4.75	15.75
6.25	19.00

A careful study of the situation, combined with closely guarded movement of the strip through the die and with coining where appropriate, may help. Sometimes, a partial bend of one interfering flange may bring it out of the way of the second flange and final forming of the first bend may do the trick.

Another bend interference is presented in Fig. 7-32. The corners of the two pointed grips are positioned against the two side flanges of the part. Perhaps these were designed to retain some material in between, while counting on the spring action of the grips. Even though no actual interference of the shape exists (per flat layout in Fig. 7-33), to bend this part will be quite a task.

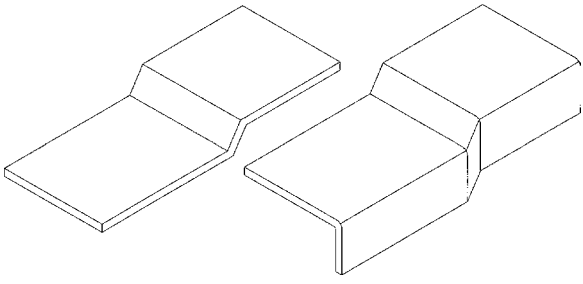

FIGURE 7-30 Joggles.

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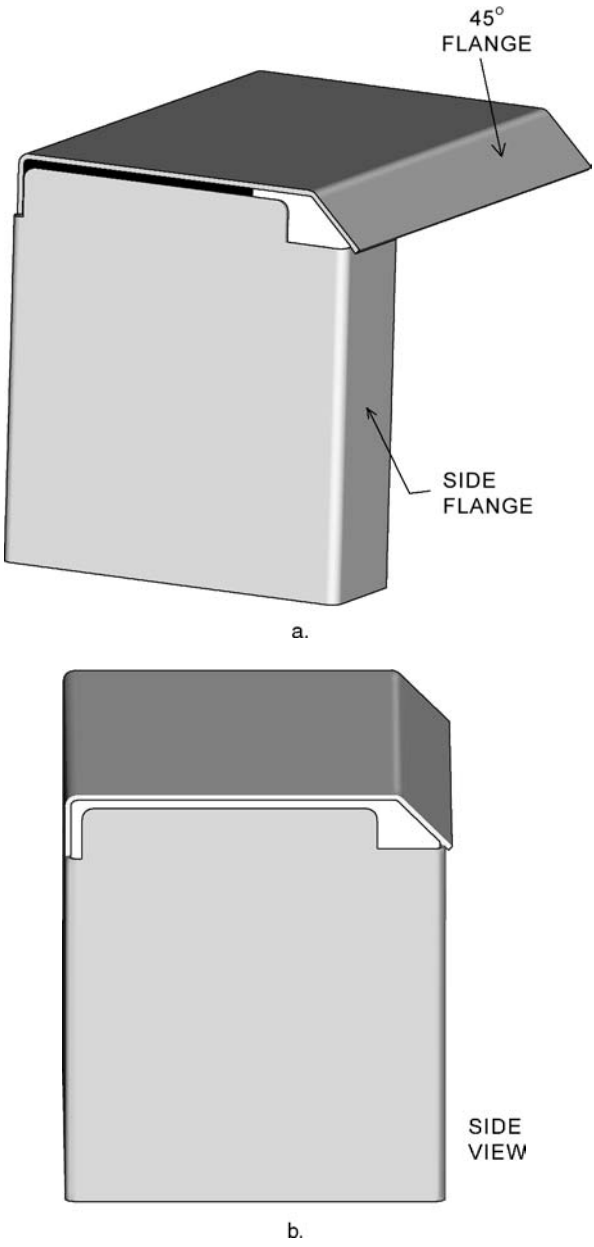

FIGURE 7-31 Interference of bends.

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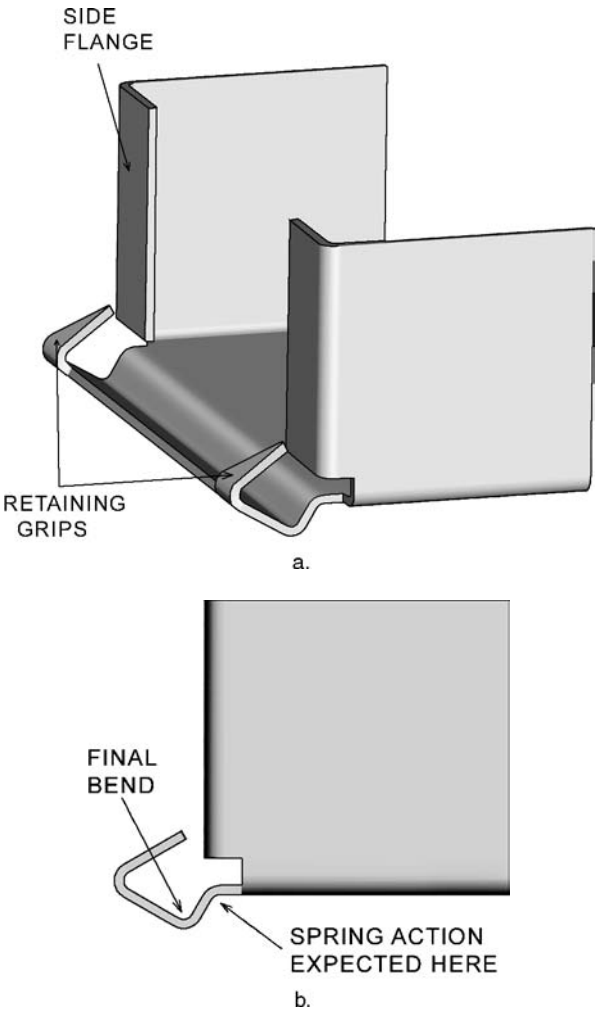

FIGURE 7-32 Bracket with retaining grips.

Of help may be to first bend the side flanges, grips, form the sides, and produce the intermediate bend first, while leaving the final bend to the end. The final bend may not need the whole length of the forming tool; only that portion which fits in between the grips may be necessary with dependence on results of testing, of course.

Where such an approach will not be feasible, a design change may be found helpful. The grips may be moved to sides, as shown in Fig. 7-34 and the spring action can be manipulated either way (either to stiffen or relax the grips' engagement) by changing the relief cuts, coring out the middle section of the spring flange, or adjusting the bend angles of the same.

In Fig. 7-35, the interference seems obvious: a narrow portion of the obtuse-angled flange clearly interferes with the shallow-angle flange. Yet the flat layout is perfectly feasible, one flange being nested within the other, with proper clearance in between (Fig. 7-36).

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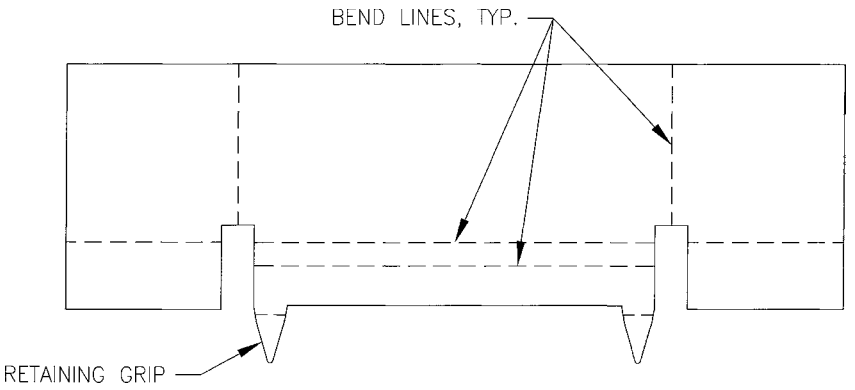

FIGURE 7-33 Flat layout of retaining bracket.

A partial forming of the sharp V-bend, followed by the forming of the shallow-bent flange and finish-forming of the V-bend may hold an answer.

In Fig. 7-37, a two-level offset bracket is shown. The design allows for mounting of the upper four corners on a different height level from that of the two lower-side shelves. The interference seems obvious when observing the formed part from the top (Fig. 7-38), but the flat layout (Fig. 7-39) proves such assumption wrong. The two heights of bent-up surfaces display a perfect clearance, which a single-height bending would not permit.

However, not only bends can interfere with each other, but so can other shapes, sections, and cuts. Presented in Fig. 7-40 is the interference of the embossed section and the bend. It is

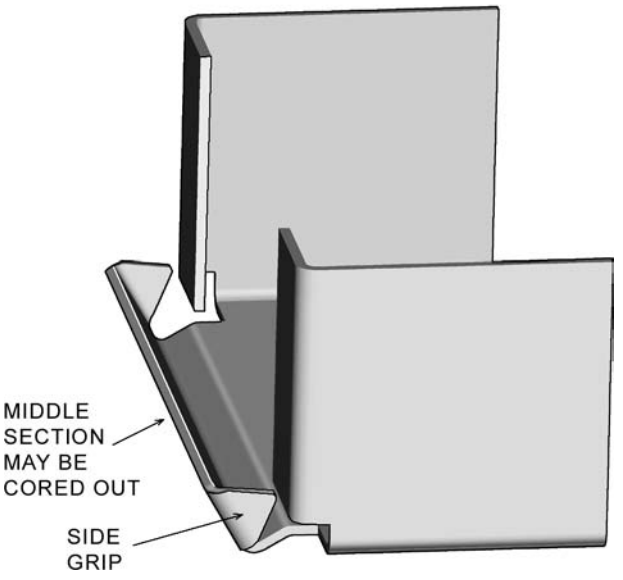

FIGURE 7-34 Alternative design of retaining bracket.

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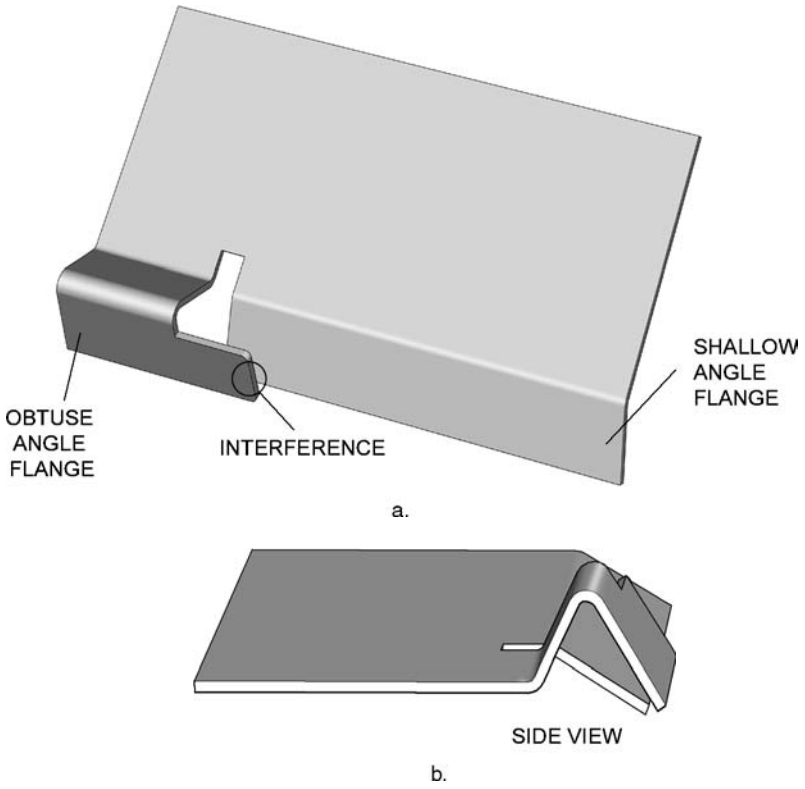

FIGURE 7-35 Interference of formed obtuse-angle flange.

quite difficult to ascertain which of these formings should be done first, in this case. The bend will certainly interfere with the already-created boss and the bending tool will have to be relieved for its shape, becoming razor-thin where it meets to bottom of the emboss. In the opposite scenario, it will be equally difficult to produce the boss so closely to the formed edge and the embossing die will have to have that portion of its circumference either razor-thin, or none. Still, such and other arrangements are being designed and produced daily.

7-2-5 Stretching of Densely Perforated Sheets

The problem of shape alteration of densely perforated surfaces has been addressed in preceding chapters. We all know by now that the piercing process cuts across the strains of material, causing them to bulge around the cut, with subsequent expansion in size and dimensional distortion of the part. Such a difference in mass distribution of heavily perforated surfaces may often be considerable, and a sequence of operations should be altered to accommodate such extremes.

Where *A* holes, shown in Fig. 7-41, are to be reasonably accurately spaced off the bottom of their flanges, the bottom rectangular surface must be perforated first. Naturally, the strain produced by such intense piercing will cause the material to expand and perhaps even to bulge. If the holes and the shape of the narrow flange are provided prior to the perforation, their location will definitely be thrown off. Therefore, these cuts must follow after the perforation is finished.

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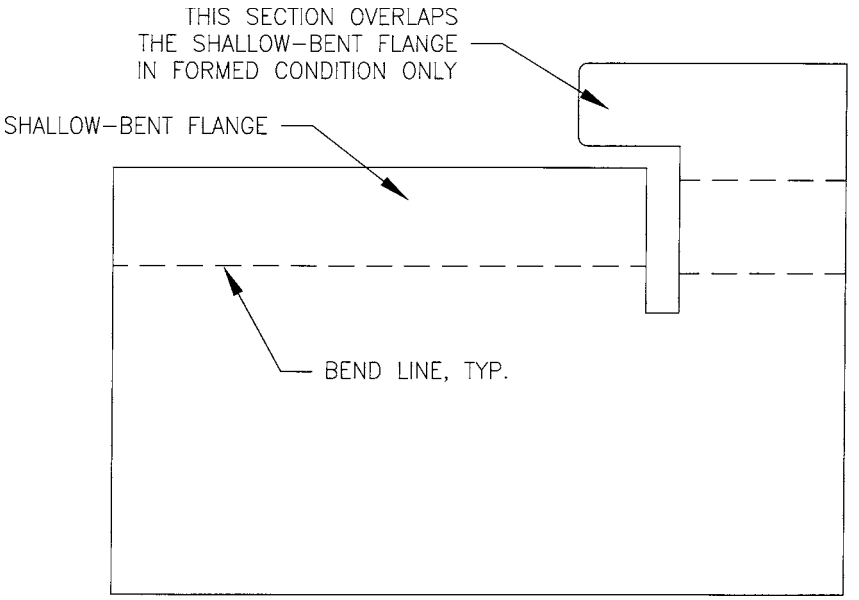

FIGURE 7-36 Flat layout of the obtuse-angle flange.

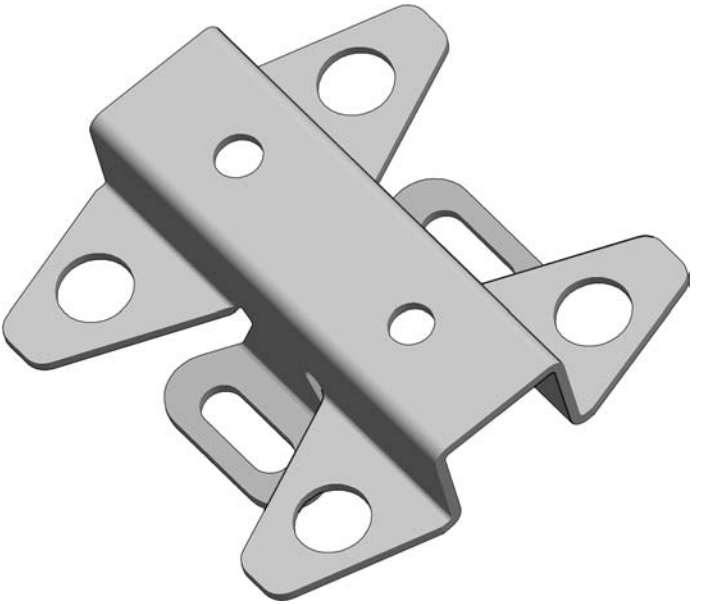

FIGURE 7-37 Offset bracket, formed part. (*Reprinted with permission from Roselle Tool and Die, Roselle Park, NJ.*)

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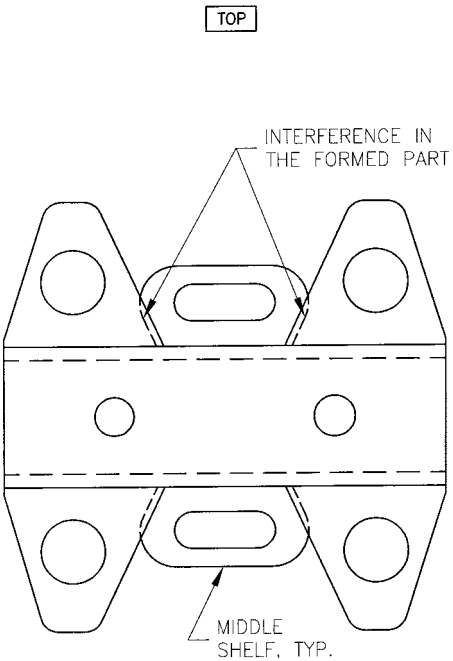

FIGURE 7-38 Offset bracket, top view of the formed part. Edges of the middle shelf are hidden under the four upper mounting corners. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

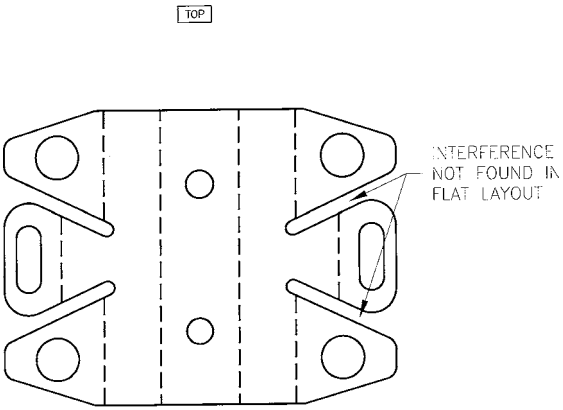

FIGURE 7-39 Offset bracket, flat layout. No interference is present. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

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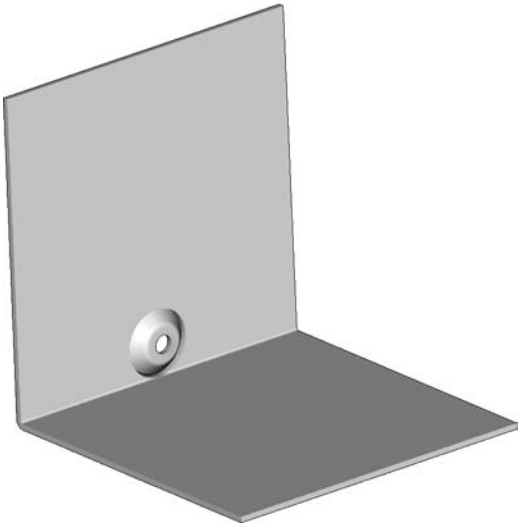

FIGURE 7-40 Interference of the embossed section and the bend.

Additionally, if the material around the flanges will be removed prior to perforation, hoping for the gap to provide the needed relief for stresses introduced by the perforating process, this may not work out well, even though a partial relief may be counted upon. The narrow middle flange with the two *A* holes will still be affected by the movement of material during piercing.

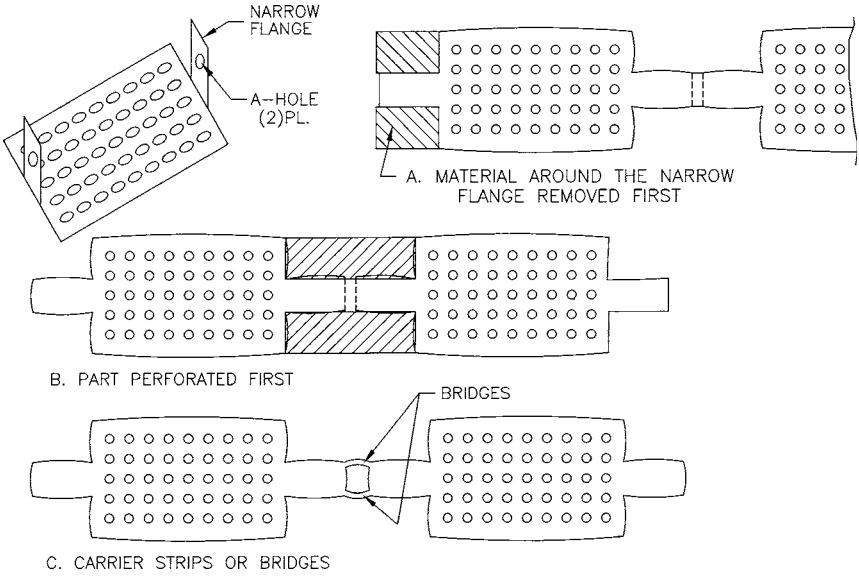

FIGURE 7-41 Expansion of perforated surface.

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But even where perforating first and removing the material around the narrow flanges afterward may not solve the problem. As shown in Fig. 4-41*B*, the lengthwise-positioned perforated part will still be found expanded in length and width, as well as perhaps bulged, after perforation. With dependence on the length of the part, these structural changes may prevent the smooth movement of the strip through the die. And when relieved by the removal of the hatched area, the cut itself may not be positioned properly, as some shifting due to the material expansion may be encountered.

Should the flanges be kept attached by small bridges of material, as shown in Fig. 7-41*C*, the still-connected parts, expanded in all directions, will tend to attack these thin strips endangering the dimensional stability of *A* holes.

Positioning the part on the strip vertically, as shown in Fig. 7-42*A* and removing most of the scrap in between, will allow for expansion in all directions. With dependence on the intensity of perforation, the strip will respond by bulging out.

Considering the part's width, we may experience a so-called "strip growth", which demonstrates itself in a difference between the strip's progression, as measured between the

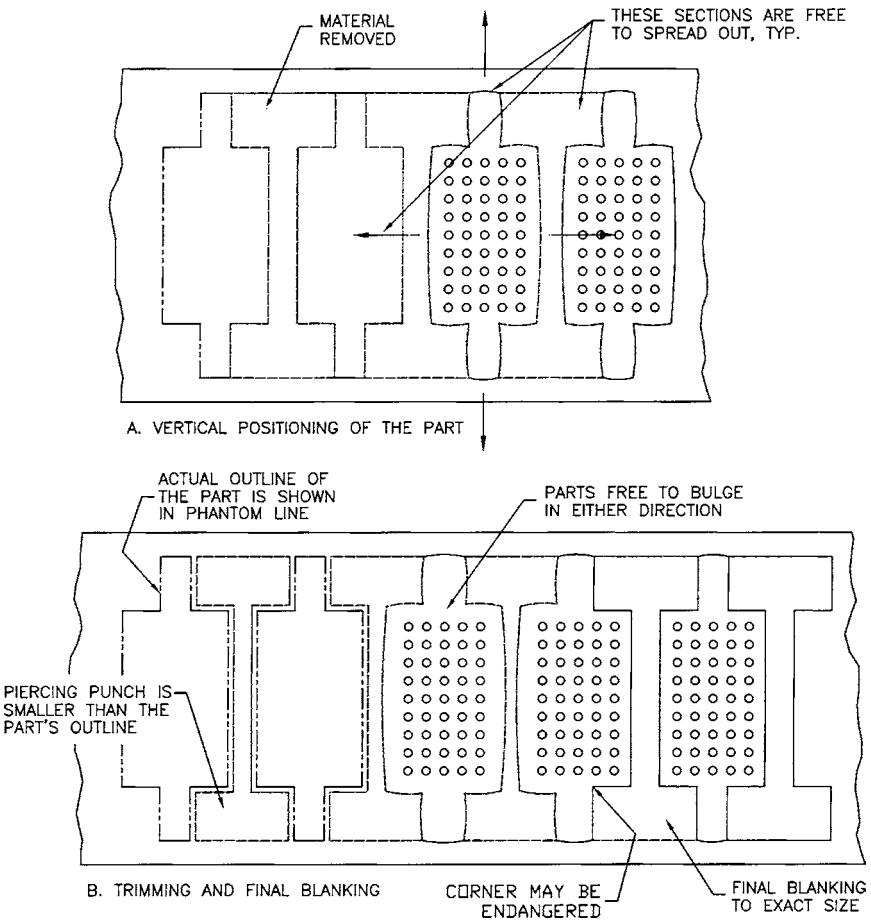
MATERIAL REMOVED
THESE SECTIONS ARE FREE TO SPREAD OUT, TYP.
A. VERTICAL POSITIONING OF THE PART
ACTUAL OUTLINE OF THE PART IS SHOWN IN PHANTOM LINE
PARTS FREE TO BULGE IN EITHER DIRECTION
PIERCING PUNCH IS SMALLER THAN THE PART'S OUTLINE
B. TRIMMING AND FINAL BLANKING
CORNER MAY BE ENDANGERED
FINAL BLANKING TO EXACT SIZE

FIGURE 7-42 Expansion of perforated surface, remedial steps.

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actual pieces, and the amount of progression of the die steel components. The bulged and distorted parts may expand and shift, gaining more width and moving out of location, with their distance being greater than that of the die components. Piloting prior to closely-toleranced piercing may be necessary. Thinner gauge parts are more readily affected by such an influence.

When considering all these changes and movement of material within the part, we should not omit to mention the condition and quality of the corner edges of cutouts, right at the root of each narrow central flange's bend. Here the bulged material may attack the sharp corner and may cause cracking of that area either in bending, or later on, in service. If perforating first, the bulging may progress as a wave into that corner and affect its inner structure. Piercing for removal of the corners later on will cut off these waves, forcing the material into a slight retreat. Cracking may occur right then. In the other situation, cutting for removal of the corners first and perforating afterward will bulge that section out, cracking the corner inwards. It will definitely be advisable to make this transition point either rounded, or provided with a relief.

Sometimes, however, where the overall dimensions of the part are of importance, trimming of the part's edges and following with a second cutting sequence which will blank the entire part out of the strip and remove the stressed edges, may be needed, as shown in Fig. 7-42*B*.

7-3 FLAT LAYOUT AND ITS ADDITIONAL USES

A correct and accurate flat layout has additional advantages in sheet-metal practice. Reproduced several times and cut out, it may serve to show a rough positioning of parts on the sheet. Their location may be altered without wasting time on sketching of every design alternative.

Placed over the finished piece, flat layout may act as a method of quick evaluation of the product's dimensional correctness. Pasted over the part, it may be used as a template in setting up some preliminary (or secondary) operations. In some instances, where a limited number of pieces is to be experimentally altered, a good flat layout could be used to show the exact location of areas of interest.

In the product-designing field, flat layout may be used as a visual aid when evaluating the part's shape and its interference with other elements of an assembly.

Flat layout drawn on *mylar* may be used for a comparison with other similar parts and their dimensional evaluation. This method of assessment is of great use especially where many similar parts are being made. Instead of checking various drawings step by step, such a quick method of evaluation can be utilized to preselect certain parts visually.

With a computerized drafting systems, flat shapes of all parts can be placed within the same file, allocating each layout to a certain layer, and positioning them all at the same distance off the origin. A quick method of comparison, unsurpassed by anything else, may be achieved this way. Computerized drafting, as opposed to a manually drawn sketch, may allow for a quick comparison of the main dimensions or of complex tooling without pulling large sheets of papers and trying to find the way through the maze of already bent-up shapes. Here, having all the parts already on the screen in flat, a visual comparison of the basic shapes, followed by a simple measurement of any questionable dimension, will ascertain quickly and efficiently any similarities or variations, if present.

The last method is useful especially in shops where a multitude of similar parts are being produced. Often a single die, perhaps with a slight alteration, may serve a purpose of producing a completely different part, without the expense of building another tool.

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CHAPTER 8
BENDING AND FORMING OPERATIONS

8-1 STRESS, STRAIN, ELONGATION, COMPRESSION

The process of material forming (i.e., *deformation*) depends on several laws, closely related to those of physics. First of all, the law of constant volume applies here. No matter how much we shrink or stretch a part, no matter how much we form it, draw it, or compress it, the basic volume we had at the beginning will always be there. True, minor volumnar changes may take place during compressive forming, but these are so minute, so small with regard to the bulk of the part that they can easily be considered irrelevant.

Another rule is pertaining to the distribution of particles in formed material. During changes of material structure, all affected segments will attempt to relocate into areas of least resistance. In other words, the material will always tend to flow where it is not obstructed, or to fill the gaps located nearby, or to conform to shapes exerting pressure upon it.

Rule number three: Every permanent deformation takes place after the changes in the material structure exceeded the maximum elastic limit of that material. However, this is not the final deformation achieved, as, after release of the applied forming pressure, the material makes an attempt to return to its previous location; we say it springs back. The complete amount of deformation is therefore equal to the sum of the elastic segment and the plastic segment of the operation, or

$$E_{\text{total}} = E_{\text{EL}} + E_{\text{PL}} \tag{8-1}$$

There are two types of deformation that can be observed during any forming process. These can be either localized, or affecting the whole part:

- Equal deformation, which is fairly even, free from excessive deviation from its mean values, and unaffected by axial orientation.
- Unequal deformation, where the shape and the size of the formed part are changed unequally. Here the differences between mean values and marginal values of the process are of greater span. During this type of deformation, many additional stresses, beneficial or detrimental, may develop.

The emergence of localized stresses within the material during unequal deformation is caused mainly by

- Unequal friction between the forming tool and the part
- Unequal temperature distribution within the part

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- Too complex a product
- Chemical differences within the material
- Mechanical properties of the material

These stresses sometimes equal each other out, for which reason they are not always observable on the surface of the part. Anyway, the human eye is mostly capable of observing only volumnar changes; those occurring on the structural or substructural level, taking place between the crystals of material, are not visible to us.

The deformative processes applied to the fabricated sheet-metal material can be numerous and their sources can be easily grouped into but several categories:

- Cutting
- Simple bending
- Forming
- Drawing
- Compressive forming
- Combinations of the above

Bending and forming are quite similar operations, the only difference being the presence of the drawing action in forming. In simple bending, a portion of the part is flexed along a straight line until a bend is obtained. In forming, the bend line may be curved, circular, or otherwise shaped. The variability of the bend line contour causes the material to expand on one side and be compressed on the opposite.

For these reasons, there are basically two types of forming operations, one producing shrink flanges and the other is used for making stretch flanges. In shrink flanges, as the name implies, the material of a flange is squeezed or compressed during forming, whereas stretch flanges are stretched and subsequently thinned (Fig. 8-1).

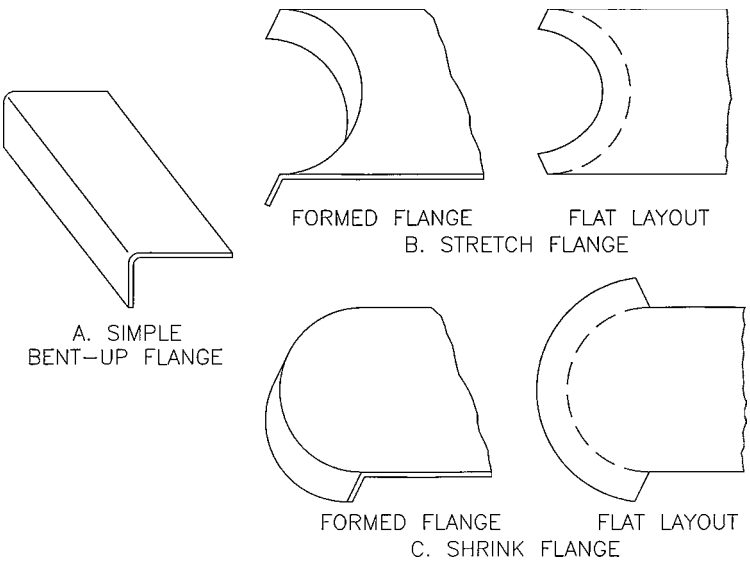

FIGURE 8-1 Types of flanges.

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BENDING AND FORMING OPERATIONS

The evaluation of the flange type should be pursued by observing the flat layout of a part, which clearly shows where the material for each flange is going to be taken from and how it will be adapted.

Bending, even though generally considered a draw-free process, does contain some minute amounts of drawing action as well. Drawing-type movement of material can be found along the circumference of the bend, where a small amount of stretching and shrinking can be seen. Some may consider this to be a lengthwise shift of various material layers with respect to each other, but the expansion or contraction of material attributable to its change in linear length with subsequent change in thickness (see Fig. 8-2) is certainly a minute amount of drawing action. True, it is an occurrence so greatly limited in scope that we may perhaps consider it negligible.

The inside portion of the bend usually does not display any considerable changes because its outline is restricted by the contact with tooling.

The cross-section of the bend and flange, in order to be considered a result of the bending operation, must maintain the same thickness as the rest of the sheet out of which it was made. An ideal situation can be found where spring-hard sheet-metal material, which—bent freely, preferably by hand, without the use of any bend-enforcing tools—forms an extremely shallow radius, returning to its original shape immediately on cessation of the applied force.

With softer metals, the tendency to succumb to the bending force is greater, and these materials do not always return to their original form and shape. The amount of spring-back, or back-returning force within the metal, is lesser in such ductile materials, making them easily altered by the application of force.

For the above reasons, bending of stiff and hard materials should utilize more acute angles than required, as the bent-up flange will always have a tendency to return to its original shape or to spring-back (Fig. 8-3). For a more detailed treatment of springback see Sec. 8-7.

Another method used for minimizing of the spring-back effect is the application of a die force against the formed part, or bottoming. This action, being in kind a coining operation, forcibly secures the bent-up portion in the desired location, while at the same time interlocking the free layers of material. Such a bend is firm and rigid, secured against most of the spring-back tendency of the material. The strain hardening, which occurs in the material owing to cold working of both the bending and coining operations, increases the strength of that section.

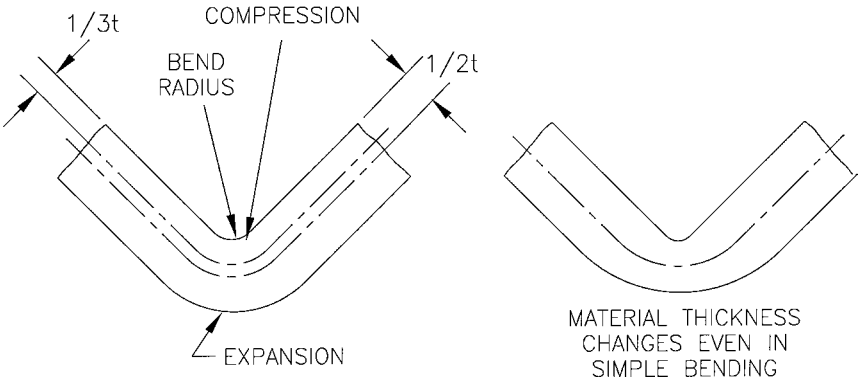

FIGURE 8-2 Location of neutral axis in bending operation.

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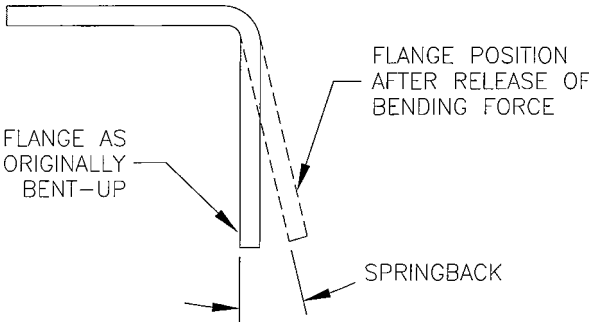

FIGURE 8-3 Springback of the bent-up flange.

8-2 BEND RADIUS

All bending and forming of sheet metal is considerably affected by two important factors:

1. Bend redius
2. Size of bend angle

With a generous bend angle, such as the one shown in Fig. 8-4*a*, any material can be formed with probably no great problems encountered, as there would be less difference between the material in flat and that already formed. Only springback will cause problems here, rendering the precision of the bend angle questionable. With shallow bends, as with large-radius bends, the results of simple bending suffer from greater differences where the final location of the bent-up flange is not secured by either overbending, bottoming, coining, or any other techniques.

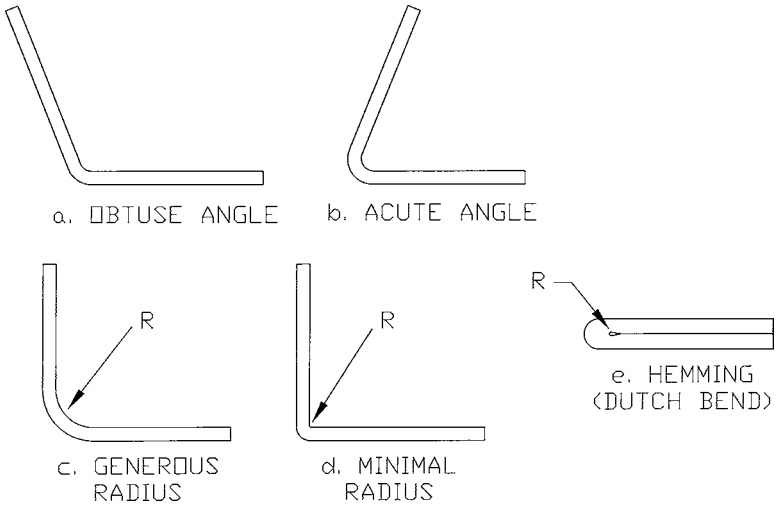

FIGURE 8-4 Various types of bends.

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With an obtuse angle, the bend radius may be specified as "sharp," and it may actually be obtained as such, for a radius in such a loose angle is extremely hard to measure, and a sharp line left by the tooling at the inner section of the bend may be considered a sharp radius.

However, as the demanded bend angle becomes sharper, other difficulties may arise, especially where it is less than 90°. A wipe die may render mostly all efforts at attaining less-than-90° bending useless, since it cannot accommodate for any sizeable overbend. Perhaps a V-die may suffice, but the springback will be there as well, and the amount of overbending needed may not always be possible.

Any bending and especially overbending needs a punch to be narrower than the gap created by the bending operation. In circumstances where the angle of the bend is too sharp, the punch cannot be made so much diminished in its mass around the tip (i.e., width), because that will impair sturdiness of the tool. The roller bending will fare similarly where very sharp bends are desired, as such great overbend will diminish the mass of the bending edge too much.

One of the few ways utilized to produce such bends is the technique used in production of hems, also called *Dutch bends*, as shown in Fig. 8-4*e*. Here the part is first bent to a 60° angle or similar (see Fig. 8-5), and flattened to desired height in second operation.

Bend radius affects the success of the bending operation profoundly. The size of it depends on the material thickness and material hardness, aside from other small, but not negligible influences. The smallest attainable bend radii for various materials are listed in Tables 8-1 through 8-4. European method of the minimum bend radius assessment utilizes a formula below.

$$BR_{\min} = kt \tag{8-2}$$

where t is the thickness of material and k is the coefficient from Table 8-5.

The "sharp bend" so often specified on drawings actually cannot be produced in sheet-metal bending. With any material other than modeling clay, should it be exposed to a strain of such excessive bending demand, it will end up fractured or outright torn.

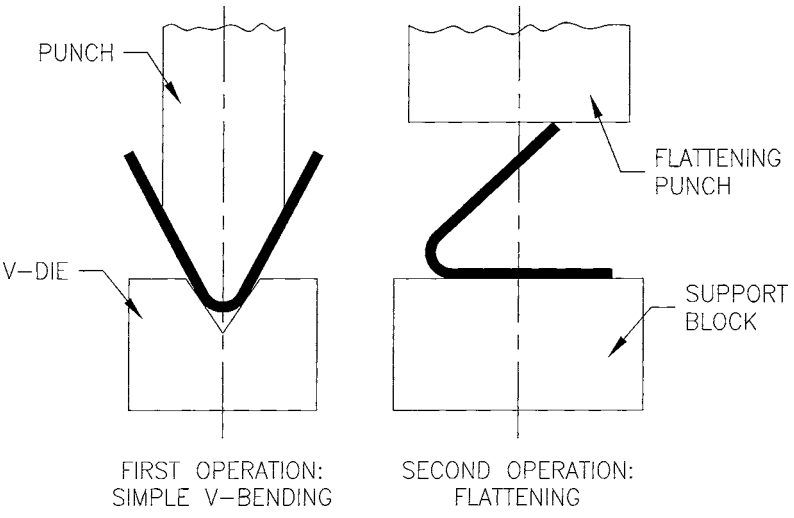

FIGURE 8-5 Overbending in two steps.

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TABLE 8-1 Minimum Bend Radii for 90° Cold Bends in Steel and Aluminum Alloys

Material type	Sheet thickness: 0.015 in. 0.4 mm	0.031 in. 0.8 mm	0.062 in. 1.5 mm	0.125 in. 3.2 mm	0.187 in. 4.75 mm
	Fractions of material thickness				
Steel:					
1020–1025	2	1½	1	1	1
4130, 8630	2	2	1½	1½	1½
1070, 1095	3–3½	3	2½	2½	2½
Aluminum:					
1100-0, H12, H14, H18; 2024-0; ALCLAD 2014-0; 3003-H12, H14, H32; 3000-0; 5005-0, H12, H14, H32, H34; 5050-0, H32, H34; 5052-0, H36; 5086-0; 5357-0, H32, H34; 5454-0; 5457-0; 5557-0; 6061-0	0	0	0	1	1
1100-H16; 5052-H34; 5456-0; 7075-0; 7178-0	0	0	0–1	1–1½	1–2
3004-H34; 5050-H34; 5052-H34; 5086-H32, H34	0	½–1	1–1½	1–1½	1–2
3003-H16; 5005-H16, H36; 5050-H36; 5154-H34, H36; 5454-H32, H34; 5456-H36; 5357-H36; 6061-T4, T42	0–1	0–1	½–1½	1–2	1½–3
1100-H18; 5052-H36; 5083-H323, H324; 5456-H323, H343; 6061-T6	0–1	½–1½	1–2	1½–3	2–4
3003-H18, H38; 5005-H18, H38; 5052-H38; 5357-H28; 5457-H38; 5657-H38	½–1½	1–2	1½–3	2–4	3–5
2024-T3, T4	1½–3	2–4	3–5	4–6	4–6
ALCLAD 2014-T3, T4; 5154-H38	1–2	1½–3	2–4	3–5	4–6
ALCLAD 2014-T6; 2024-T36; 7075-T6; 7178-T6	2–4	3–5	3–5	4–6	5–7

Sheet-metal material, even where bent at the sharpest corner possible, will still maintain a trace of a bend radius, as shown in Fig. 8-6*a*. This small curvature will offset the formed flange away from the body of the die, as shown in detail P. Such a gap will shift the flange into the way of the forming punch, which, on interference, will either shear that portion off, or will make an attempt at drawing or ironing of the wall.

There is always some amount of a bend radius present in a formed flange. Even a 180° bend, such as a hem (also called a *Dutch bend*), shown in Fig. 8-4*e*, will contain a

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TABLE 8-2 Minimum Bend Radii for 90° Cold Bends for Stainless Steel

		Sheet thickness Values are fractions of stock thickness	
Material type	Temper	Up to 0.050 in. [1.2 mm]	0.051–0.187 in. [1.26–5.0 mm]
301, 302, 304, 316	Annealed	90° and 180° = ½	90° and 180° = 1
301, 302	¼ hard	90° and 180° = ½	90° and 180° = 1
301, 302	½ hard	90° and 180° = 1	90° and 180° = 1
301, 302	Full hard	90° and 180° = 2	
316	¼ hard	90° and 180° = 1	90° and 180° =1

slight bend radius, unless completely flattened out by a coining operation, to the point of cracking.

Some may be optimistic about using a wipe-forming die with no corner radius and an angled die edge, as shown in Fig. 8-6*b*, to produce the desired sharp corner in sheet metal. Such a tool will certainly cut more easily through the metal than form it.

A method of producing a sharp corner is shown in Fig. 8-6*c*. Here the flanges are offset beyond the bend radius, leaving a gap where the material of the corner radius would normally appear. In assemblies where some other part must surely bank against this corner and no relief in that part is possible, the offset bend radius may be of help.

The size of bend radius varies with cold bending, as opposed to bending with the addition of heat. It is known that with heating of steel, its properties change, and sharper bends may be attained in previously unyielding materials. Also the required bending force will be lessened and springback values lowered, since these depend on temperature of the process.

TABLE 8-3 Minimum Bend Radii for Low-Carbon and Low-Alloy Steel

Material Thickness, in. (mm)	SAE 1020–1025 in. (mm)	SAE 4130 and 8630 (Annealed) in. (mm)	SAE 1070 and 1095 in. (mm)
0.016 (0.41)	0.03 (0.8)	0.03 (0.8)	0.06 (1.5)
0.020 (0.51)	0.03 (0.8)	0.03 (0.8)	0.06 (1.5)
0.025 (0.64)	0.03 (0.8)	0.03 (0.8)	0.06 (1.5)
0.030 (0.76)	0.03 (0.8)	0.06 (1.5)	0.09 (2.3)
0.035 (0.89)	0.06 (1.5)	0.06 (1.5)	0.09 (2.3)
0.042 (1.07)	0.06 (1.5)	0.06 (1.5)	0.13 (3.3)
0.050 (1.27)	0.06 (1.5)	0.09 (2.3)	0.13 (3.3)
0.062 (1.57)	0.06 (1.5)	0.09 (2.3)	0.16 (4.1)
0.078 (1.98)	0.09 (2.3)	0.13 (3.3)	0.19 (4.8)
0.093 (2.36)	0.09 (2.3)	0.16 (4.1)	0.25 (6.4)
0.109 (2.77)	0.13 (3.3)	0.16 (4.1)	0.31 (7.9)
0.125 (3.18)	0.13 (3.3)	0.19 (4.8)	0.31 (7.9)
0.156 (3.96)	0.16 (4.1)	0.25 (6.4)	0.38 (9.7)
0.187 (4.75)	0.19 (4.8)	0.31 (7.9)	0.50 (12.7)

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TABLE 8-4 Minimum Bend Radii for Copper Alloys

Material type	Material thickness, in.	Material thickness, mm	Material condition	Bend across the grain	Bend at 45° to the grain	Bend parallel with the grain
Copper	0.021	[0.50]	Half-hard	0.031 in. [0.75 mm]	0.031 in. [0.75 mm]	0.046 in. [1.20 mm]
Brass, yellow	0.021–0.062	[0.50–1.50]	Half-hard	Sharp	Sharp	0.015 in. [0.38 mm]
Brass, yellow	0.042	[1.00]	Full-hard	Sharp	0.015 in. [0.38 mm]	0.031 in. [0.75 mm]
Brass, yellow	0.042	[1.00]	Spring temper	0.046 in. [1.20 mm]	0.218 in. [5.55 mm]	0.218–0.250 in. [5.55–6.35 mm]
Brass, red	0.021–0.062	[0.50–1.50]	Half-hard	Sharp	Sharp	0.015 in. [0.38 mm]
Brass, red	0.042	[1.00]	Full-hard	0.015 in. [0.38 mm]	0.031 in. [0.75 mm]	0.093 in. [2.35 mm]
Brass, red	0.042	[1.00]	Spring temper	0.062 in. [1.57 mm]	0.187 in. [4.75 mm]	0.437–0.500 in. [11.00–12.70 mm]
Phosphor bronze, 5%	0.021–0.062	[0.50–1.50]	Half-hard	Sharp	Sharp	0.015 in. [0.38 mm]
Phosphor bronze, 5%	0.042	[1.00]	Full-hard	0.062 in. [1.57 mm]	0.062 in. [1.57 mm]	0.125 in. [3.20 mm]
Phosphor bronze, 5%	0.042	[1.00]	Spring temper	0.093 in. [2.35 mm]		
Phosphor bronze, 8%	0.021–0.062	[0.50–1.50]	Half-hard	Sharp	Sharp	0.015 in. [0.38 mm]
Phosphor bronze, 8%	0.042	[1.00]	Full-hard	0.031 in. [0.75 mm]	0.125 in. [3.20 mm]	
Phosphor bronze, 8%	0.042	[1.00]	Spring temper	0.093 in. [2.35 mm]	0.250 in. [6.35 mm]	0.437–0.500 in. [11.00–12.70 mm]
Cartridge brass, 70%	0.021–0.062	[0.50–1.50]	Half-hard	Sharp	Sharp	0.015 in. [0.38 mm]
Cartridge brass, 70%	0.042	[1.00]	Full-hard	0.015 in. [0.38 mm]	0.031 in. [0.75 mm]	0.046 in. [1.20 mm]
Cartridge brass, 70%	0.042	[1.00]	Spring temper	0.062–0.125 in. [1.57–3.20 mm]	0.218 in. [5.55 mm]	0.218–0.250 in. [5.55–6.35 mm]

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TABLE 8-5 Coefficient k of the Minimum Bend Radius

	Material condition			
	Annealed		Heat-treated	
	Relationship bend/grain		Relationship bend/grain	
Material	⊥	∥	⊥	∥
Deep drawing steel	0.05	0.2	0.2	0.5
Steel, AISI 1010, 1040	0.1	0.5	0.5	1.0
Steel, AISI 1015, 1020	0.2	0.6	0.6	1.2
Steel, AISI 1049	0.3	0.8	0.8	1.5
Steel, AISI 1064	0.7	1.3	1.3	2.0
Copper	0.1	0.2	1.0	2.0
Brass	0.05	0.2	0.4	0.8
Zinc	0.5	1.0		
Aluminum	0.05	0.2	0.3	0.8
Aluminum, hard	1.0	1.5	3.0	4.0
Electron, Mg-metal	2.0	3.0	7.0	9.0
Titanium	0.5	1.0	3.0	5.0

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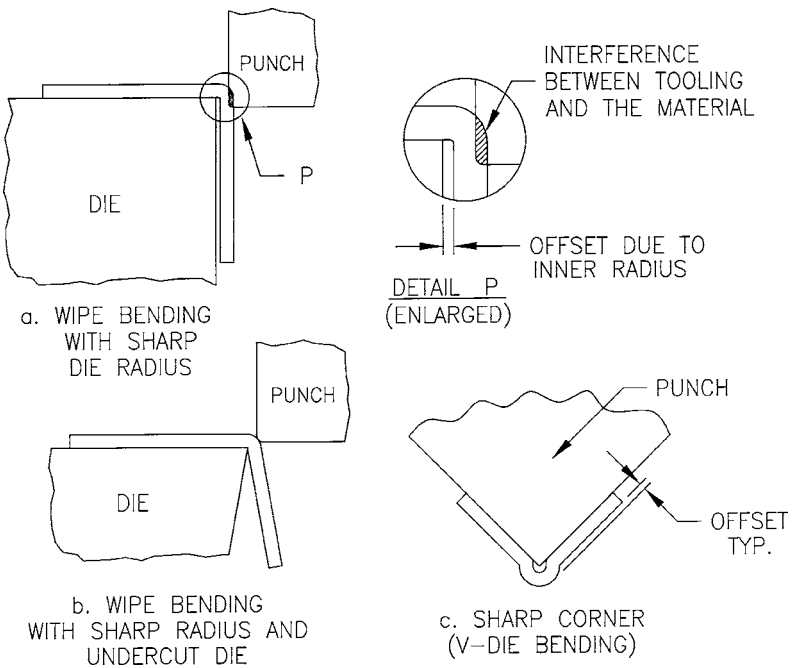

FIGURE 8-6 The theory of zero-radius bending.

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8-3 RADIUS OF FORMING TOOLS

The forming radius of punches and dies determines the size of the plasticized area created by the bending process. Additionally, it influences the quality and cosmetic appearance of the bend. For example, in wipe-bending or U-die bending, the sharper a radius of the forming edge will be used, the more severely it will force the material to flow, creating marks on its surface.

During the forming process, as the punch progresses down, the first minute radius thus created is soon being tugged upon and re-formed, by the continuously descending punch, and another radius is being formed in its stead. The sharper the bending radius, the greater amount of such formations and re-formations the material has to go through. If excessive, such process results in greater springback, greater work hardening, with a possibility of tearing the bend apart.

The strain of bending operation, also called *bending strain*, is a function of the bend radius and the thickness of formed material. With a smaller bend radius of the die, the formed metal must stretch its outer layers much more severely, and compressing its inner layers equally, while becoming formed. The proper die radius should also be selected in proportion to material thickness, following an R/t ratio guidelines. (See the graph in Fig. 8-7).

The lower the R/t ratio, the more stress it generates in the formed material. With more stress, the strain hardening becomes substantial and a demand for the forming force increases. Breakage of parts occurs where the forming force reaches the limits of the material.

The basic dimensional requirements for various types of bending tools are given in Fig. 8-8. These numbers are generally used for bending of material across the grain; where bending along the grain line is unavoidable, an increase of approximately 20 to 25 percent in die radius is needed.

In bending and forming, the cooperation between the punch and die cannot be overemphasized. For example, in wipe forming, or U-die forming—if too long a gap between the radius of the punch and that of the die is encountered (i.e., the distance measured with the die closed), excessive scarring of the formed part will result, combined with difficult stripping

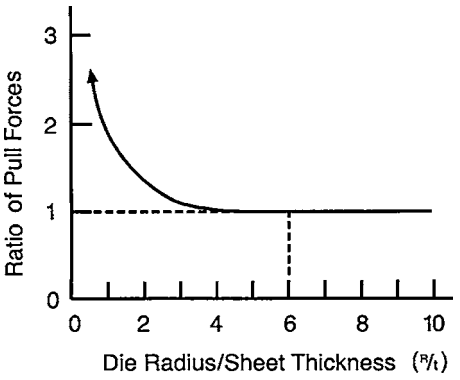

FIGURE 8-7 Decreasing the die radius/sheet thickness. Decreasing the die radius to sheet thickness ratio (R/t) below 4 causes the force required to pull the sheet metal over the die radius to increase rapidly. Material used: AKDQ steel in the common 0.03 [0.75 mm] to 0.05 in. [1.25 mm] range.

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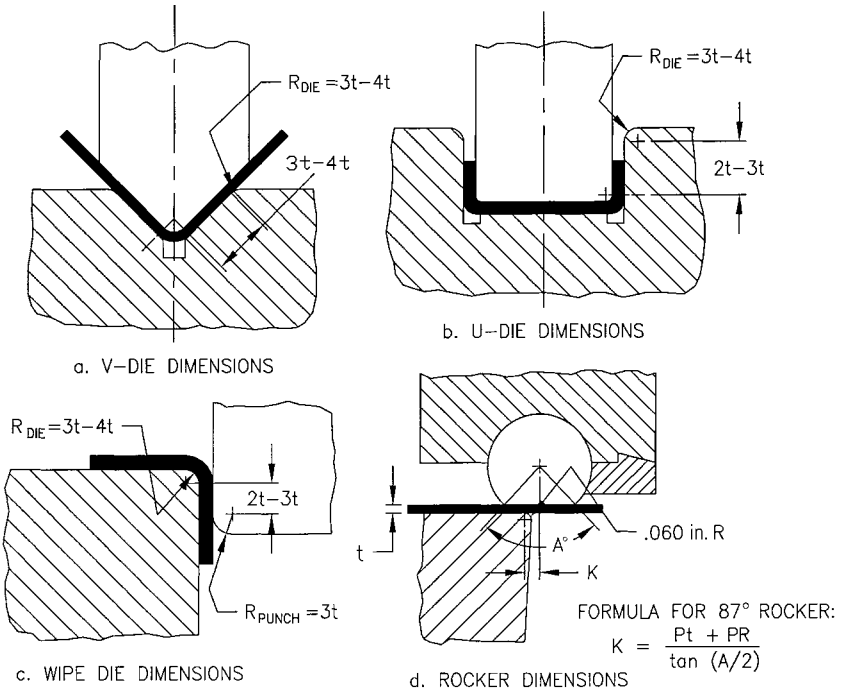

FIGURE 8-8 Generally recommended dimensioning of bending tools. (Pictures *a, b, c* are from: *Practical Aids For Experienced Die Engineer, Die Designer, and Die Maker, 1980. Reprinted with permission from Arntech Publishers, Jeffersontown, KY.*) (*Picture d is reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)

and perhaps even with breakage of tooling, and the like. Where too short a section is used, inadequate forming and obtuse bends may be produced.

8-3-1 Radius of the Forming Die

The bottom corner die radii in a V-die and U-channel die have no use in metal forming and should be left out completely. Actually, a sharp corner, or a milled relief slot is quite okay there, as the material will not flow into this area anyway. In bending, as in drawing, the material stays wrapped around the punch. It is the punch that needs to have the tip rounded, so that it does not break through the tensed material.

8-3-2 Radius of the Forming Punch

Advices on the forming punch radius vary throughout the industry. Most often, in U-die bending and V-bending, the part's drawing dictates the size of the bend radius. But where not stated, manufacturers may use whatever suits them the best. Some recommend to have the tip of the forming punch radiused to the tune of t to $1.5t$, where t is the material thickness. Elsewhere, especially in sheet-metal fabricating field, a habit of bending everything with R 0.031 in. [0.75 mm] to R 0.062 in. [1.50 mm] prevails. Perhaps this is due to the fact that press brakes used for such bending run usually at a much slower rate than most progressive dies. However, where a $\frac{1}{8}$ in. [3.25 mm] thick material will be bent with $0.5t$ radius tooling, the

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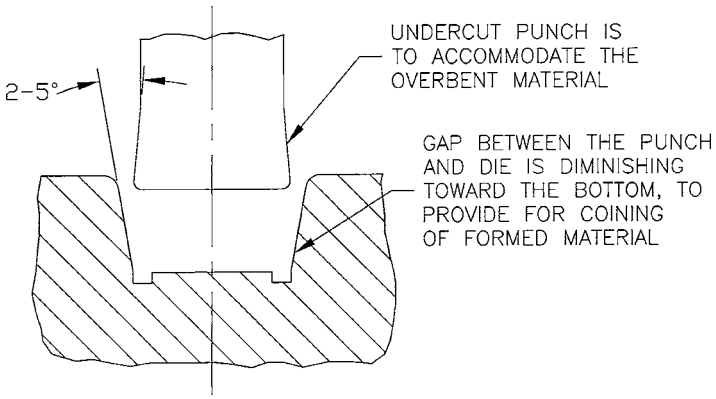
2–5°
UNDERCUT PUNCH IS TO ACCOMMODATE THE OVERBENT MATERIAL
GAP BETWEEN THE PUNCH AND DIE IS DIMINISHING TOWARD THE BOTTOM, TO PROVIDE FOR COINING OF FORMED MATERIAL

FIGURE 8-9 Gap between forming punch and die.

tensile strain of the upper layers of the formed material will increase considerably and breakages may occur in many such cases.

Along with general dimensioning rules for different types of bending tools, the recommended radius range of the wipe forming punch is given in Fig. 8-8*c*. This type of a punch is subject to similar rules like those pertaining to the bending radius of the die.

8-3-3 Gap Between the Forming Punch and Die

The space between forming punch and die exerts yet another significant influence on the result of bending operation. As such, it is also a subject to many advices, which vary in scope from the material thickness' width of a gap, or t spacing, up to $1.2t$ and perhaps even more. Others recommend this distance to be 0.002–0.005 in. [0.05–0.13 mm] smaller than the maximum limit of the fabricated material thickness, including its tolerance range.

Sometimes, in an attempt to eliminate the springback, the space between the punch and die in U-channel forming, may be diminished toward the bottom of the groove (see Fig. 8-9), which causes slight ironing of the part's sides. The ironed material is misplaced in the direction of the upper portion of the flange (i.e., leg), forcing it to lean toward the punch. The punch is purposely relieved to accommodate for such a movement. The misplaced material becomes solidified on cessation of ironing and it allows for lesser springback, often turning out parts at exactly 90°.

8-3-4 The Speed of Forming Operation

Surely, the forming speed affects the forming process too, even though mostly in a negative way. For with increase of the forming speed, the speed-generated heat due to forming rises as well, and greater material hardening in steel can be observed. In some aluminum alloys an exact opposite may take place.

8-4 EDGE FORMABILITY

The *edge formability* is the ability of material to be formed without fracturing or thinning around the edges of holes. This characteristic is experimentally assessed by stretching a

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circular blank containing a round hole in the middle. The stretching is done by the punch with a flat bottom, and the edge of the centrally located opening is observed for the appearance of cracks.

Interestingly enough, it was noticed that with the equally dispersed punch pressure, the hole does not remain round. With hot-rolled low-carbon steel used for drawing, the largest opening size was found at a 45° angle off the grain line. In cold-rolled steel of the drawing type, the largest diameter was found at the location parallel with the grain direction or at 0° off the grain line, whereas in cold-rolled high-strength low-alloy steels the *smallest diameter* could be found at 90° off the grain line.

Edge formability is going to be increasingly important owing to the escalated use of high-strength steel. This is because such a mechanical property of the material is crucial in evaluation of sheet-metal behavior in forming and bending operations.

Edge cracking in bending originates already in blanking or punching operations, and it is often present with other kinds of material separating processes, such as trimming, perforating, or cutoff. The appearance of cracks is closely related to the shear of sheet-metal material in cutting, where the stretched stock is separated via connecting action of the cracks, one set of which originates on top of the material thickness (by the edge of a punch) and the other set comes up from the bottom (from the die edge) as shown in Fig. 6-2. Varying the punch-die tolerance range may sometimes be helpful, but it cannot always be counted upon. Sometimes, only careful studies and tryout runs can show if the edge will crack in subsequent bending or not.

Surprisingly, laser-cutting is not always a culprit blamable for edge cracking, even though a laser cut can produce some localized damage in the area where it enters the cutting path, or around some curves and sharp corners. Whenever a laser path is drastically diverted in any direction, the influence of the laser beam is increased proportionally to its deceleration, which is necessary for its change of path.

One way to solve the problems with edge formability and edge cracking is by producing all bends and doing all the forming first, and leaving the blanking operation to the absolute end. Unfortunately, most of the time this approach cannot be utilized.

Often, the speed of the forming process can increase the cracks' emergence by heating the material to higher temperatures during faster speeds. Where this is the case, an evaluation of severity of forming operation should be attempted and the results calculated using the formula below:

$$S_F = 100\left(\frac{t_f - t_i}{t_i}\right) \tag{8-3}$$

where S_F = strain of forming (severity of forming), in percents
t_i = thickness of material, initial
t_f = thickness of material, final

Varying the press speed and varying the type of lubricant can sometimes bring about an improvement.

8-5 NEUTRAL AXIS IN BENDING

The neutral axis of the material is supposed to do exactly what its name implies: to remain neutral during the bending process and to conform to neither side of the altered material.

However, the neutral axis does not remain totally neutral, as it shifts slightly in the forming operation, even though its length remains the same (Fig. 8-10). Because of the deformation of the bent-up material, the neutral axis moves toward the center of the bend radius.

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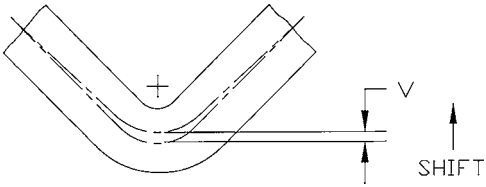

FIGURE 8-10 Shift of the neutral axis in bending.

This shift, even though small in size, may be of importance in some areas of the industry, for which reason it is included in the following chart. Its amount is based on the ratio of the bend radius and material thickness:

R/t	0.1	0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
v	0.0125	0.0135	0.015	0.0165	0.0175	0.018	0.0185	0.019	0.019

where *v* is the change in the neutral axis location in inches, which is directed toward the origin of the bend radius.

For purposes of calculation of the flat size of a part, the location of neutral axis, presented here as an ingredient of various formulas and tables, has been altered with each type of bending operation performed. These percentile values are based on actual tests and years of experience of toolmakers, designers, and engineers.

8-6 TYPES OF BENDING OPERATIONS

Bending of sheet metal can be accomplished through utilization of several manufacturing processes. First of all, the distinction can be made as far as the bending part's support is concerned: There is supported bending and unsupported bending.

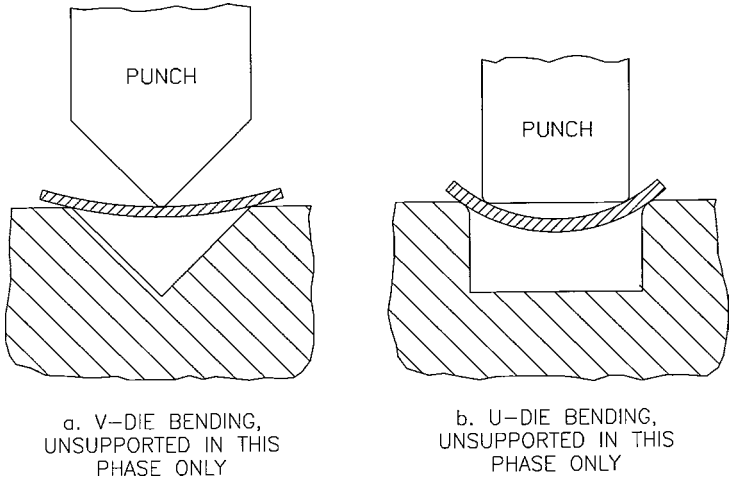

FIGURE 8-11 Unsupported bending.

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BENDING AND FORMING OPERATIONS

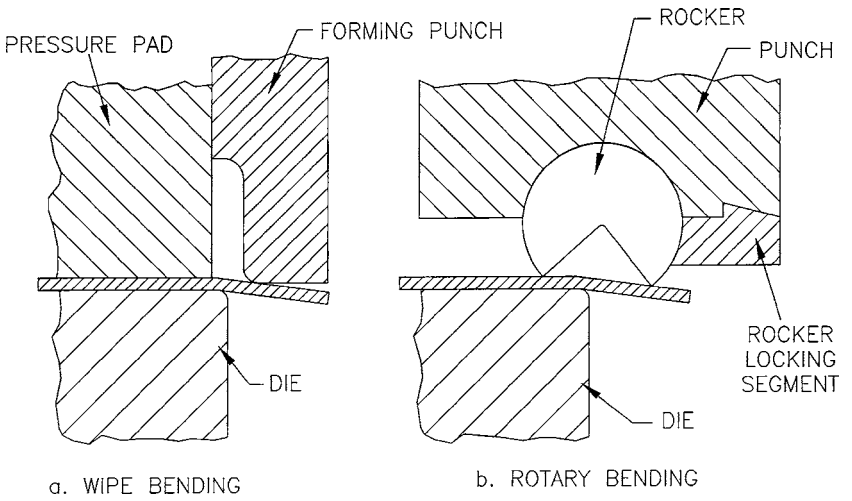

FIGURE 8-12 Supported and partially supported bending.

Unsupported bending is similar to the process of stretching, where a flat piece of metal, retained in a die, stretches along with the application of tool pressure.

U-die and V-die bending are both considered unsupported bending processes at their beginning stages, as shown in Fig. 8-11. As the bending process continues, and the material is pulled down into the recess, all the way down, the bending becomes supported, as shown in Figs. 8-12 and 8-13.

Supported bending may be considered any bending where a spring-loaded pad, is included for support of the formed part (see Fig. 8-13*c*).

Supported bending has one advantage over the other methods, the added benefit of coining. As already mentioned, after a part is formed, the material's tendency to return to its original shape may be prevented by overbending its flanges and coining, or bottoming. Overbending consists of bringing the flange to a more acute angular distance than necessary. Coining applies a squeezing pressure to the strains of material, securing them in their present location.

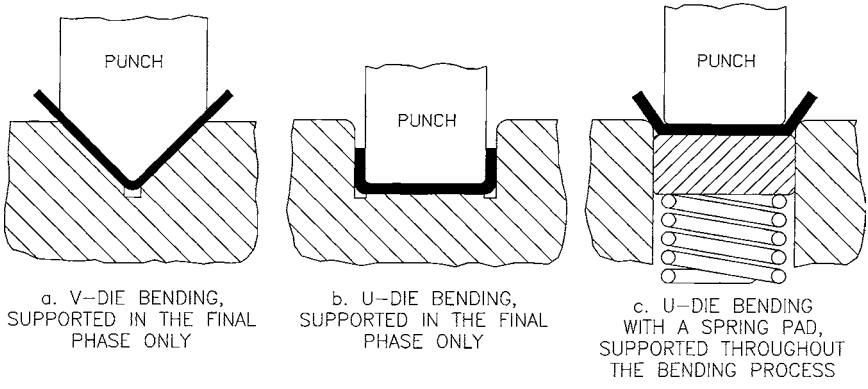
PUNCH
a. V–DIE BENDING, SUPPORTED IN THE FINAL PHASE ONLY
PUNCH
b. U–DIE BENDING, SUPPORTED IN THE FINAL PHASE ONLY
PUNCH
c. U–DIE BENDING WITH A SPRING PAD, SUPPORTED THROUGHOUT THE BENDING PROCESS

FIGURE 8-13 Supported bending.

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8-6-1 V-Die Bending

Even though V-die bending is probably the most inaccurate of all bending processes, it is widely used throughout the industry. The reasons are obvious: The tooling is simple and may be used for more than one flange and for more than one part.

During V-die bending, the punch slides down, coming first to a contact with the unsupported sheet metal. By progressing farther down, it forces the material to follow along, until finally bottoming on the V shape of the die. As may be observed, at the beginning of this process, the sheet is unsupported, but as the operational cycle nears its end, the bent-up part becomes totally supported while retained within the space between the punch and die (Fig. 8-14).

To calculate the length of a piece in flat, when only bent-up dimensions are given (which is the usual way of dimensioning sheet-metal parts), various formulas that follow may be utilized. These calculations are quite similar, their only difference being the anticipated variation of the location of the neutral axis with respect to the bending or forming process used.

Calculation of the bend allowance for a soft steel material, using a V-die bending or forming process, shifts the neutral axis into one-third of the material thickness. The formula is

$$BA_{V\text{-die}} = C\left(R_{\text{in}} + \frac{t}{3}\right) \tag{8-4}$$

where BA = bend allowance (see also Table 8-6)
R_{in} = inside radius of the bend
t = material thickness
C = constant, depending on the angle of the bend. For 90° bends, this value is 1.5708. For bends of different angularity, see Table 8-7

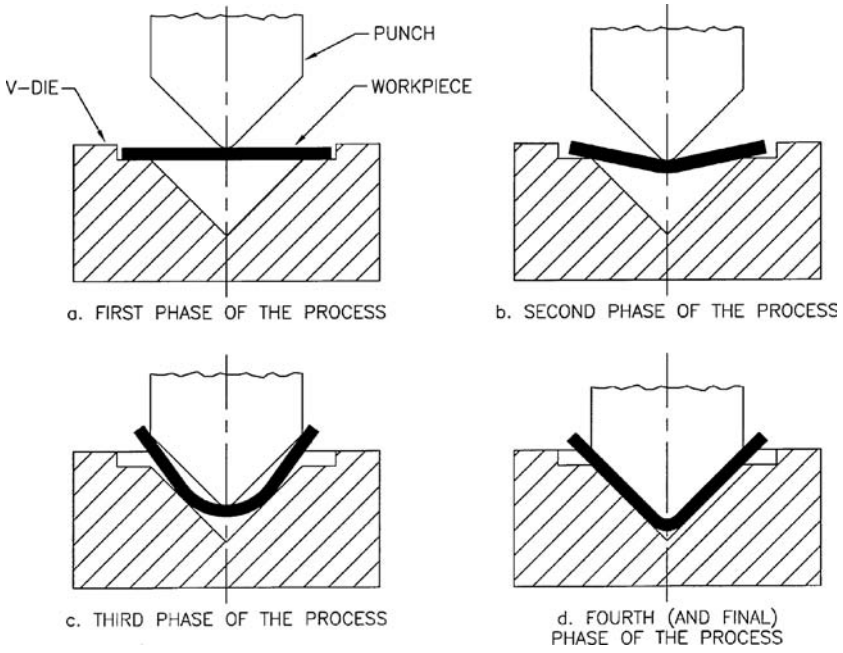
PUNCH
V–DIE
WORKPIECE
a. FIRST PHASE OF THE PROCESS
b. SECOND PHASE OF THE PROCESS
c. THIRD PHASE OF THE PROCESS
d. FOURTH (AND FINAL) PHASE OF THE PROCESS

FIGURE 8-14 V-die bending: description of a process. (*Reprinted with permission from Zdeněk Macháček and Karel Novotný, Speciální Technologie I., published by ČVUT, Brno, Czech Republic.*)

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TABLE 8-6 Bend Allowance Chart for 90°. Bends in Annealed Steel, V-Die Bending

Material thickness	Bend radius																
	0.015	0.031	0.062	0.093	0.125	0.156	0.187	0.218	0.250	0.281	0.312	0.343	0.375	0.406	0.437	0.468	0.500
Inches																	
0.015	0.031	0.057	0.105	0.154	0.204	0.253	0.302	0.350	0.401	0.449	0.498	0.547	0.597	0.646	0.694	0.743	0.793
0.018	0.033	0.058	0.107	0.156	0.206	0.254	0.303	0.352	0.402	0.451	0.500	0.548	0.598	0.647	0.696	0.745	0.795
0.024	0.036	0.061	0.110	0.159	0.209	0.258	0.306	0.355	0.405	0.454	0.503	0.551	0.602	0.650	0.699	0.748	0.798
0.031	0.040	0.065	0.114	0.162	0.213	0.261	0.310	0.359	0.409	0.458	0.506	0.555	0.605	0.654	0.703	0.751	0.802
0.036	0.042	0.068	0.116	0.165	0.215	0.264	0.313	0.361	0.412	0.460	0.509	0.558	0.608	0.657	0.705	0.754	0.804
0.047	0.048	0.073	0.122	0.171	0.221	0.270	0.318	0.367	0.417	0.466	0.515	0.563	0.614	0.662	0.711	0.760	0.810
0.054	0.052	0.077	0.126	0.174	0.225	0.273	0.322	0.371	0.421	0.470	0.518	0.567	0.617	0.666	0.715	0.763	0.814
0.062	0.056	0.081	0.130	0.179	0.229	0.278	0.326	0.375	0.425	0.474	0.523	0.571	0.622	0.670	0.719	0.768	0.818
0.078	0.064	0.090	0.138	0.187	0.237	0.286	0.335	0.383	0.434	0.482	0.531	0.580	0.630	0.679	0.727	0.776	0.826
0.093	0.072	0.097	0.146	0.195	0.245	0.294	0.342	0.391	0.441	0.490	0.539	0.587	0.638	0.686	0.735	0.784	0.834
0.109	0.081	0.106	0.154	0.203	0.253	0.302	0.351	0.400	0.450	0.498	0.547	0.596	0.646	0.695	0.744	0.792	0.842
0.125	0.089	0.114	0.163	0.212	0.262	0.310	0.359	0.408	0.458	0.507	0.556	0.604	0.655	0.703	0.752	0.801	0.851
0.140	0.097	0.122	0.171	0.219	0.270	0.318	0.367	0.416	0.466	0.515	0.563	0.612	0.662	0.711	0.760	0.808	0.859
0.156	0.105	0.130	0.179	0.228	0.278	0.327	0.375	0.424	0.474	0.523	0.572	0.620	0.671	0.719	0.768	0.817	0.867
0.171	0.113	0.138	0.187	0.236	0.286	0.335	0.383	0.432	.0482	0.531	0.580	0.628	0.679	0.727	0.776	0.825	0.875
0.187	0.121	0.147	0.195	0.244	0.294	0.343	0.392	0.440	0.491	0.539	0.588	0.637	0.687	0.736	0.784	0.833	0.883
0.203	0.130	0.155	0.204	0.252	0.303	0.351	0.400	0.449	0.499	0.548	0.596	0.645	0.695	0.744	0.793	0.841	0.892
0.218	0.138	0.163	0.212	0.260	0.310	0.359	0.408	0.457	0.507	0.556	0.604	0.653	0.703	0.752	0.801	0.849	0.900
0.234	0.146	0.171	0.220	0.269	0.319	0.368	0.416	0.465	0.515	0.564	0.613	0.661	0.712	0.760	0.809	0.858	0.908
0.250	0.154	0.180	0.228	0.277	0.327	0.376	0.425	0.473	0.524	0.572	0.621	0.670	0.720	0.769	0.817	0.866	0.916

(*Continued*)

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TABLE 8-6 Bend Allowance Chart for 90°. Bends in Annealed Steel, V-Die Bending (*Continued*)

Material thickness	Bend radius																
	0.50	0.75	1.50	2.50	3.50	4.00	4.75	5.50	6.25	7.00	8.00	8.75	9.50	10.25	11.00	12.00	13.00
Millimeters																	
0.40	0.99	1.39	2.57	4.14	5.71	6.49	7.67	8.85	10.03	11.21	12.78	13.95	15.13	16.31	17.49	19.06	20.63
0.50	1.05	1.44	2.62	4.19	5.76	6.55	7.72	8.90	10.08	11.26	12.83	14.01	15.18	16.36	17.54	19.11	20.68
0.63	1.12	1.51	2.69	4.26	5.83	6.61	7.79	8.97	10.15	11.33	12.90	14.07	15.25	16.43	17.61	19.18	20.75
0.80	1.20	1.60	2.78	4.35	5.92	6.70	7.88	9.06	10.24	11.41	12.99	14.16	15.34	16.52	17.70	19.27	20.84
1.00	1.31	1.70	2.88	4.45	6.02	6.81	7.98	9.16	10.34	11.52	13.09	14.27	15.45	16.62	17.80	19.37	20.94
1.20	1.41	1.81	2.98	4.56	6.13	6.91	8.09	9.27	10.45	11.62	13.19	14.37	15.55	16.73	17.91	19.48	21.05
1.40	1.52	1.91	3.09	4.66	6.23	7.02	8.19	9.37	10.55	11.73	13.30	14.48	15.66	16.83	18.01	19.58	21.15
1.60	1.62	2.02	3.19	4.76	6.34	7.12	8.30	9.48	10.66	11.83	13.40	14.58	15.76	16.94	18.12	19.69	21.26
2.00	1.83	2.23	3.40	4.97	6.55	7.33	8.51	9.69	10.86	12.04	13.61	14.79	15.97	17.15	18.33	19.90	21.47
2.20	1.94	2.33	3.51	5.08	6.65	7.44	8.61	9.79	10.97	12.15	13.72	14.90	16.07	17.25	18.43	20.00	21.57
2.80	2.25	2.64	3.82	5.39	6.96	7.75	8.93	10.11	11.28	12.46	14.03	15.21	16.39	17.57	18.74	20.32	21.89
3.00	2.36	2.75	3.93	5.50	7.07	7.85	9.03	10.21	11.39	12.57	14.14	15.32	16.49	17.67	18.85	20.42	21.99
3.50	2.62	3.01	4.19	5.76	7.33	8.12	9.29	10.47	11.65	12.83	14.40	15.58	16.76	17.93	19.11	20.68	22.25
4.00	2.88	3.27	4.45	6.02	7.59	8.38	9.56	10.73	11.91	13.09	14.66	15.84	17.02	18.20	19.37	20.94	22.51
4.50	3.14	3.53	4.71	6.28	7.85	8.64	9.82	11.00	12.17	13.35	14.92	16.10	17.28	18.46	19.64	21.21	22.78
5.00	3.40	3.80	4.97	6.55	8.12	8.90	10.08	11.26	12.44	13.61	15.18	16.36	17.54	18.72	19.90	21.47	23.04
5.50	3.67	4.06	5.24	6.81	8.38	9.16	10.34	11.52	12.70	13.88	15.45	16.62	17.80	18.98	21.16	21.73	23.30
6.00	3.93	4.32	5.50	7.07	8.64	9.42	10.60	11.78	12.96	14.14	15.71	16.89	18.06	19.24	20.42	21.99	23.56
7.00	4.45	4.84	6.02	7.59	9.16	9.95	11.13	12.30	13.48	14.66	16.23	17.41	18.59	19.77	20.94	22.51	24.09

BENDING AND FORMING OPERATIONS

TABLE 8-7 Bend Allowance Constants for Bends Across the Grain Only

Angle *A*	*BA* constant *C*	Angle *A*	*BA* constant *C*
10 seconds	0.0029	35°	0.6109
30 seconds	0.0087	40°	0.6981
1°	0.0175	45°	0.7854
2°	0.0349	50°	0.8728
3°	0.0524	55°	0.9599
4°	0.0698	60°	1.0472
5°	0.0873	65°	1.1345
10°	0.1745	70°	1.2217
15°	0.2618	75°	1.3090
20°	0.3491	80°	1.3963
25°	0.4363	85°	1.4835
30°	0.5236	90°	1.5708

Values may vary with different types of material. For bends smaller than 90° use the constants given. For bends greater than 90° combine the constant for 90° with the constant for the angular excess.

The bend allowance per Eq. (8-4) would be further used to calculate the total length of the part, L_{total} (see Fig. 8-15), as follows:

$$L_{\text{total}} = BA + A + B \tag{8-5a}$$

Numerous adaptations of V-die bending exist throughout the manufacturing field. Some examples are shown in Fig. 8-16.

8-6-2 U-Die Bending

In this type of bending, the process begins with a strip or sheet of metal positioned over a U-shaped opening or an insert of such a shape. As the punch comes down, it contacts the

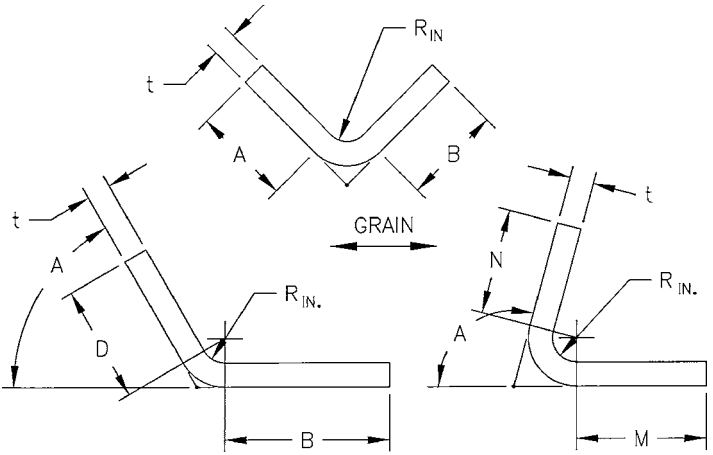

FIGURE 8-15 Dimensioning for bend allowance calculation for bends across the grain, V-die bending.

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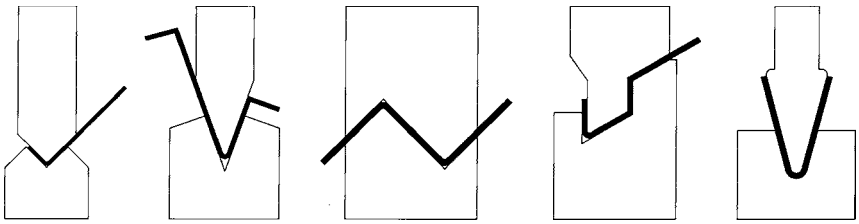

FIGURE 8-16 V-die bending samples.

sheet-metal material first and pulls it along on further descent, forcing it into the U-shaped opening.

Calculation of the bend allowance for a bent or formed flange, made of hard steel, considers the neutral axis to be located in the middle of the material thickness. Such a formula is as follows:

$$BA = C\left(R_{\text{in}} + \frac{t}{2}\right) \tag{8-6}$$

where R_{in} = inside radius of the bend
t = material thickness
C = constant, depending on the angle of the bend. For 90° bends, this value is 1.5708. For bends of different angularity, see Table 8-7.

The bend allowance is further used the same way as shown in Eq. (8-5*a*), where all abbreviations are based on Fig. 8-17.

The bend allowance formula for soft steel, formed or bent in a U die (Fig. 8-18), or for a condition where the metal is drawn over the edge of either punch or die:

$$BA_{\text{U-die}} = C\left(R_{\text{in}} + \frac{t}{4}\right) \tag{8-7}$$

The bend allowance is further used to calculate the total length of the part, using the altered formula (8-5*a*):

$$L_{\text{total}} = BA + A + B + D \tag{8-5b}$$

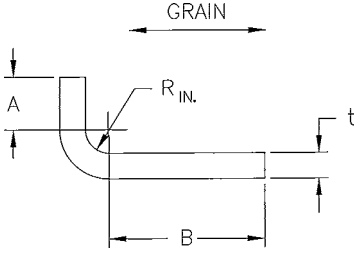

FIGURE 8-17 Dimensioning for bend allowance calculation for 90° bends, partial U-die bending.

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BENDING AND FORMING OPERATIONS

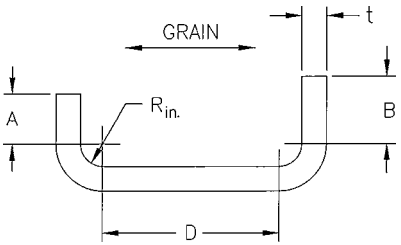

FIGURE 8-18 Dimensioning for bend allowance calculation for 90° bends, U-type bending.

The minimum length of a U-forming punch should be equal to the inner length of the formed part, plus 2*t*.

Three segments of a bending process, shown in Fig. 8-19, depict an unsupported forming in the first stage, followed by a stretching of the material due to the punch pressure in the second stage. The last operation, bottoming, shows the tendency of the bulging bottom to allocate the excess material within the corners of the part. A subsequent bending of the sides toward the body of a punch may be observed.

In U-shaped die forming, the difference in the outcome is introduced with an addition of a spring-loaded pressure pad underneath the part (see Fig. 8-20). The blank, when pulled by the punch into the die opening, is supported by the pressure pad already at the beginning of the forming operation.

When the punch-metal-pad sandwich finally bottoms, the formed part remains the same, with no bulging or distortion of any kind.

In bending with pressure pad, an additional variable, the amount of spring pressure of the pad, exerts its influence on success of the operation. Contrary to what may be expected, a weak spring pressure can often produce parts with straight edges, whereas a strong spring pressure causes the emergence of more-than-90° bends, shown in Fig. 8-20*b*. A possible explanation is as follows.

In the bending process shown in Fig. 8-20*a*, the weak spring pressure allows for a slight distortion of material under the punch. The punch pulls onto those layers of material being the closest, forcing them to flow away from the sides toward the bottom of the recess, where it compresses them. Such an incoming wave of material forces the content of layers located on the opposite of the material thickness to flow up toward the sides, a shift which is further aided by the weak spring pad pressure. This material heading up is more likely to be

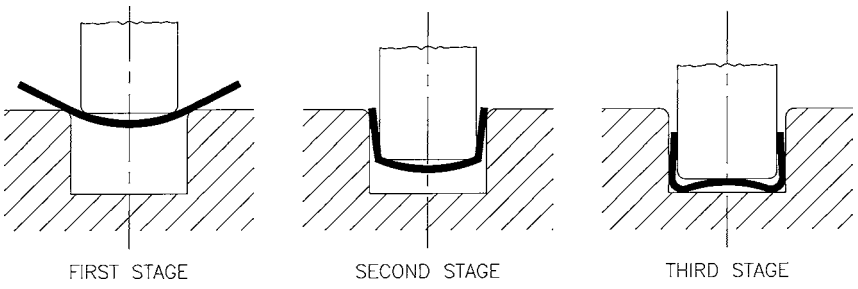

FIGURE 8-19 U-die bending process.

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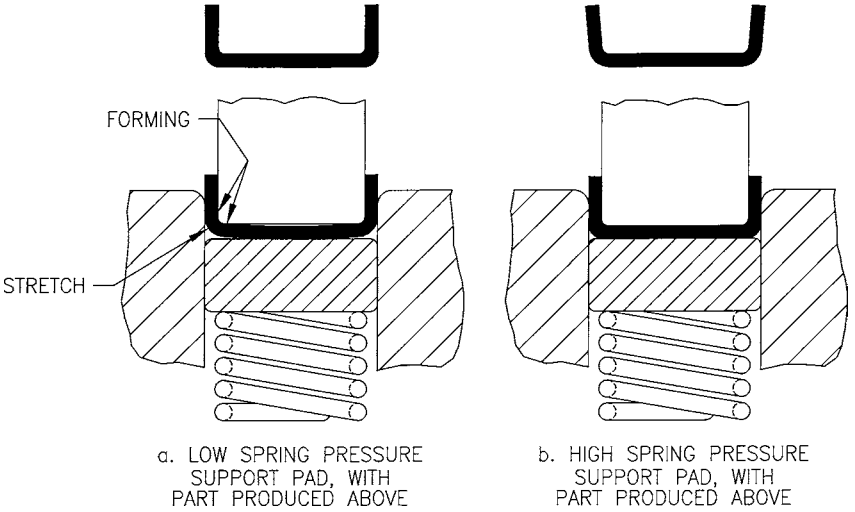
FORMING
STRETCH
a. LOW SPRING PRESSURE SUPPORT PAD, WITH PART PRODUCED ABOVE
b. HIGH SPRING PRESSURE SUPPORT PAD, WITH PART PRODUCED ABOVE

FIGURE 8-20 Pressure pad application in forming.

only stretched, yet it creates a slight bulge in the sides, which on release of the forming pressure would not allow the sides to springback as much as these would normally do.

The case shown in Fig. 8-20*b*, uses high spring pressure for holding the material firmly between the punch and the pad. The sides are formed and a flow of metal from those areas is achieved. However, the material cannot relocate to the bottom section, being prevented by the force of spring pad, and may eventually be forced to crowd the upper portion of the side. For the same reason, the movement of material from the opposite layers of metal thickness under the punch cannot be achieved either. Only on release of the punch pressure, some material from the bottom flows belatedly into the bend areas increasing the amount of displaced material already there, which causes the side flanges to springback away from the punch.

8-6-3 Wipe Bending

In the wipe-bending method of producing bends, the blank is retained in a fixed position by the spring-loaded pressure pad (Fig. 8-21). The forming punch comes down toward the exposed flange and bends it during its further descent.

The formula to use for this type of bend allowance is as follows:

$$BA_{\text{wipe}} = C\left(R_{\text{in}} + \frac{t}{5}\right) \tag{8-8}$$

where R_{in} = inside radius of the bend
t = material thickness
C = constant, depending on the angle of the bend. For 90° bends, this value is 1.5708. For bends of different angularity, see Table 8-7.

The bend allowance is further used to calculate the total length of the part, as shown in Eqs. (8-5*a*) or (8-5*b*).

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BENDING AND FORMING OPERATIONS

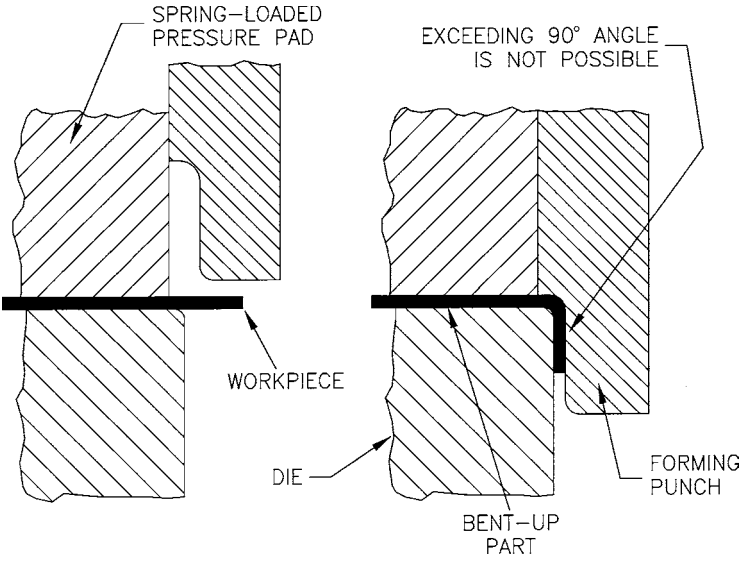

FIGURE 8-21 Wipe bending process.

8-6-4 Rotary Bending

Rotary bending has several advantages over traditional types of bending. Not only does it utilize 50 to 80 percent less bending force than wipe bending process (Fig. 8-22), it generally does not need a pressure pad for retention of the material, as the rocker provides for it automatically (Fig. 8-23).

As the tool comes down, the rocker lands on the material, positioning itself with one edge over the die and with the other over the gap. Coming farther down, its pressure bends down the flange, but it does not stop at 90°; it continues farther to attain a 3° overbend as a protection against spring-back.

The Ready Bender® rocker is shaped like a cylinder, with an angular portion of its entire length cut out. It is made from fully hardened (58HRc), cryogenically tempered S-7 tool steel. Both rocker and its saddle are CNC ground for precision and interchangeability.

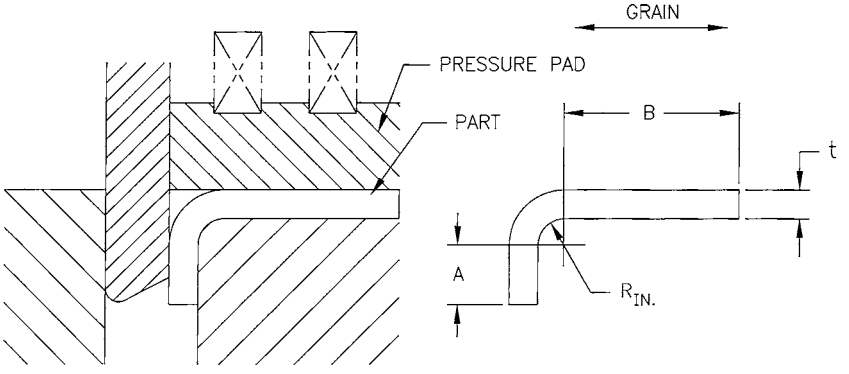

FIGURE 8-22 Dimensioning for bend allowance calculation, wipe bending.

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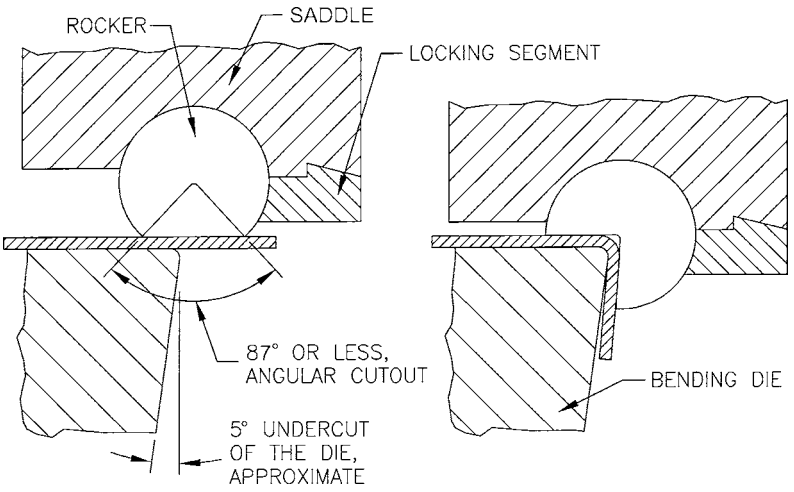

FIGURE 8-23 Rotary bending process using Ready Benders®. (*Reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)

Ready Benders® regulate the springback of the material by overbending, rather than coining. As a result, a lesser amount of material from the radius area becomes relocated, which is the reason for a greater bend allowance than that of wipe bending. The general formula for the bender's bend allowance is

$$BA_{\text{bender}} = 0.01745PA(PR + 0.43PT) \tag{8-9}$$

where all values are as shown in Fig. 8-24.

Ready Technology Co. has another tool called a Ready Hemmer®, which can form a 90° bend completely flat in a single stroke of the press, as shown in Fig. 8-25. This tool can be used not only for flat hems, but also when forming over an insert, as shown in Fig. 8-26. The advantages are easier handling of the part in the die, and reducing a hemming operations to two press strokes versus the normal three press strokes with a conventional hemming tool.

Producing stiffening ribs with rotary benders leaves the parts free from galling or distortions (Fig. 8-27). When compared to wipe-produced ribs, the benders do not need the

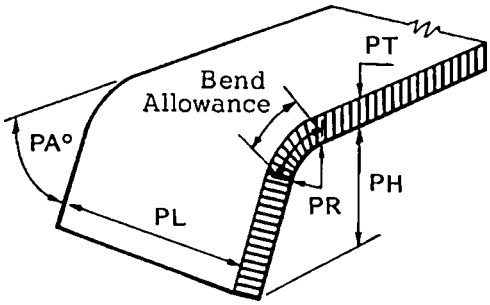

FIGURE 8-24 Bend allowance in rotary bending. (*Reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)

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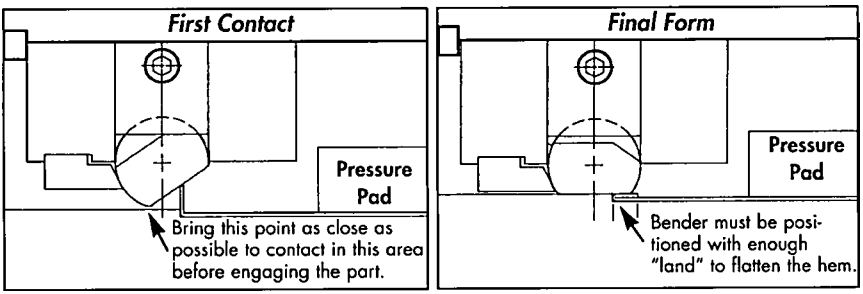

First Contact
Pressure Pad
Bring this point as close as possible to contact in this area before engaging the part.
Final Form
Pressure Pad
Bender must be positioned with enough "land" to flatten the hem.

FIGURE 8-25 The Ready Hemmer® and its function. (*Reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)

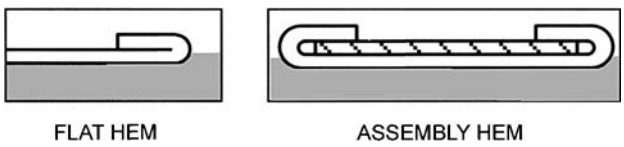
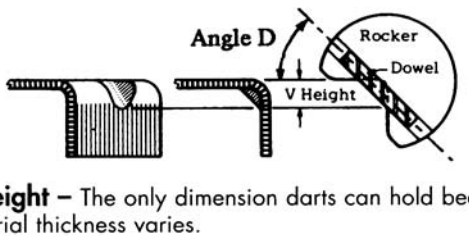


FIGURE 8-26 Flat hem and a hem formed over an insert. (*Reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)



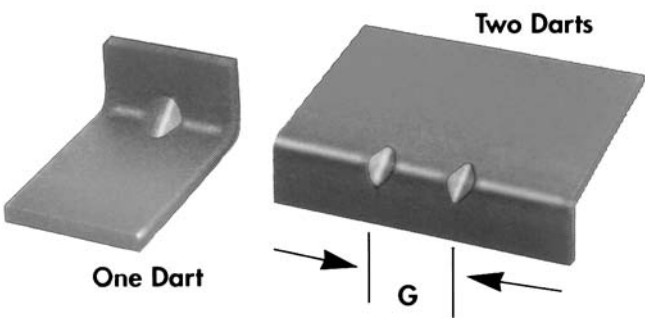


FIGURE 8-27 Edge-stiffening ribs produced with Ready Benders®. (*Reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)

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amount of maintenance a wipe punch would require and the consistency of the forming process is greater.

8-6-4-1 Bending With Rotary Inserts. This type of bending is actually an alternative of U-die application, with rotary inserts placed at the corners of a die (Fig. 8-28). The inserts are spring-loaded, allowing the material to land upon them, and retracting under the press force. On release, inserts force the part up.

One advantage of this process is the possibility of overbending the flanges as a protection against spring-back occurrence.

8-6-4-2 Bending With a Pivoted Roller. The roller is attached to the punch plate by a pin. As the upper section of the die slides down, the roller engages the material, forcing it down and under the nose in the die block (see Fig. 8-29).

8-6-5 Bending With Flexible Tooling

Bending with flexible tooling utilizes rubber or urethane forming pads instead of hard-metal tooling (Figs. 8-30 to 8-33). Its advantage lies in the possibility of forcing the flexible tooling material to fill gaps and undercuts, taking the in-between sheet-metal strip along.

Forces necessary for bending with flexible tooling are higher than those needed for conventional bending methods. These differences have not yet been assessed because of the great amount of variables involved. The strain-hardening tendency of the material will have to be evaluated in comparison with the elastic properties of the flexible forming material, aside from other influencing aspects.

With V-die bending utilizing elastic material, the bending process is rather different from the one using hard tooling. First, the sheet-metal material is compressed by the nose of a tool, elongating tangentially under its pressure (see Fig. 8-33). The pressure of the elastic pad is restricted to quite a small area immediately surrounding the tool impression.

The radius of the bent-up part usually ends up being larger than that of the tooling. Enlarging the radius of the V-die does not readily solve the problem, as a considerable enlargement is needed for the part to follow the shape of the punch. However, there are no directions to follow in such an undertaking, as all the work on a subject has been arrived at experimentally, with not enough data collected yet.

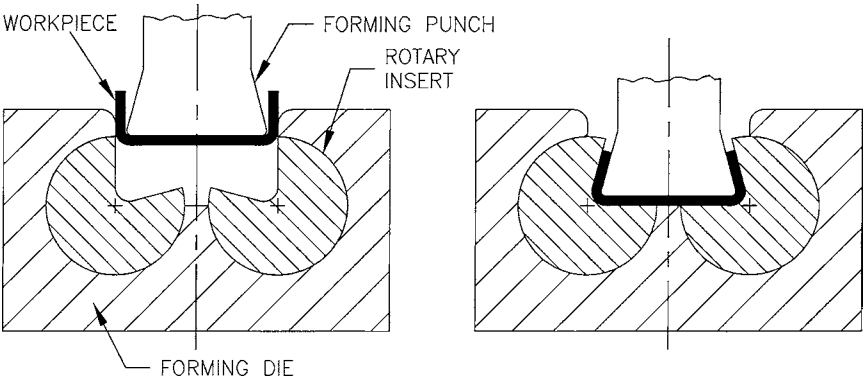

FIGURE 8-28 Bending with rotary inserts.

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BENDING AND FORMING OPERATIONS

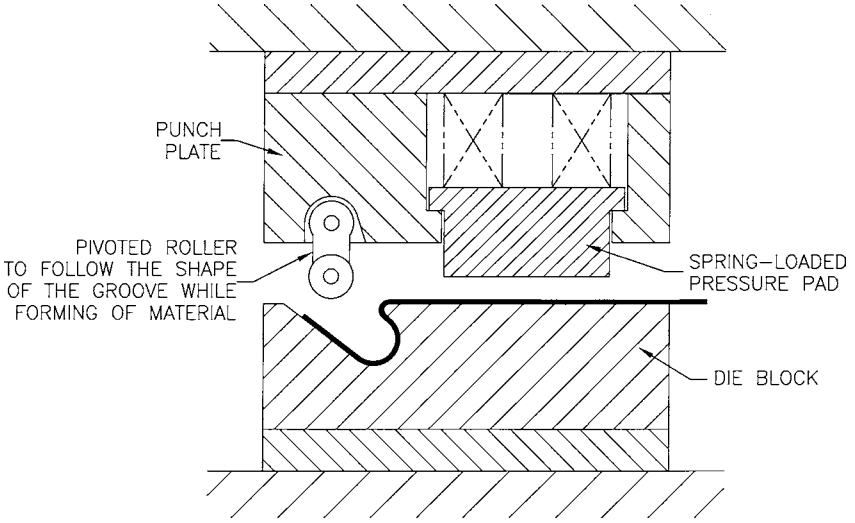
PUNCH PLATE
PIVOTED ROLLER TO FOLLOW THE SHAPE OF THE GROOVE WHILE FORMING OF MATERIAL
SPRING–LOADED PRESSURE PAD
DIE BLOCK

FIGURE 8-29 Roller-type bending die.

8-6-6 Forming With Cams

Cams are unique arrangements, which, as driven by the power of a press, can produce a form of the side of a part, pierce openings from various directions, and even produce spring-back-free bends. Cams achieve these tasks by transforming the vertical motion of the press ram into a horizontal or inclined motion of the cam slide. Of course, this all is done at a cost. The cost of cam mechanisms is always higher than the cost of regular punches and

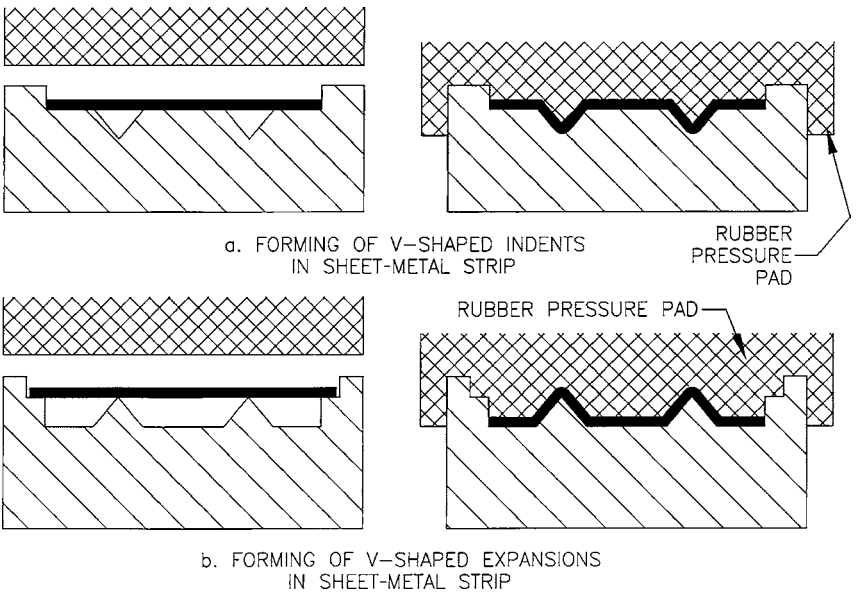
a. FORMING OF V–SHAPED INDENTS IN SHEET-METAL STRIP
RUBBER PRESSURE PAD
RUBBER PRESSURE PAD
b. FORMING OF V–SHAPED EXPANSIONS IN SHEET-METAL STRIP

FIGURE 8-30 Forming with flexible tooling.

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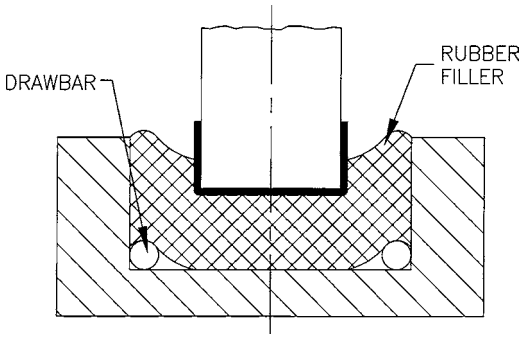

FIGURE 8-31 Bending with flexible tooling.

dies, which is the reason why die designers turn to the cam-involving solutions only when everything else fails.

The two cam dies shown in Fig. 8-34 represent two types of cam movements: (a) that with a spring-operated return of the slide, and (b) that with a cam-operated return. In each case, the punch only rough-forms the part, while the cam-driven slide finishes the forming. The movement of the cam in the first illustration is guided over adjustable and replaceable inserts, which, when attached in strategic locations, are capable of prolonging the life of the cam mechanism.

In cam design, a 45° minimum and 50° preferred angle of inclination of driving surfaces is important. In Fig. 8-35, the piercing punch is guided by a horizontally-oriented guide

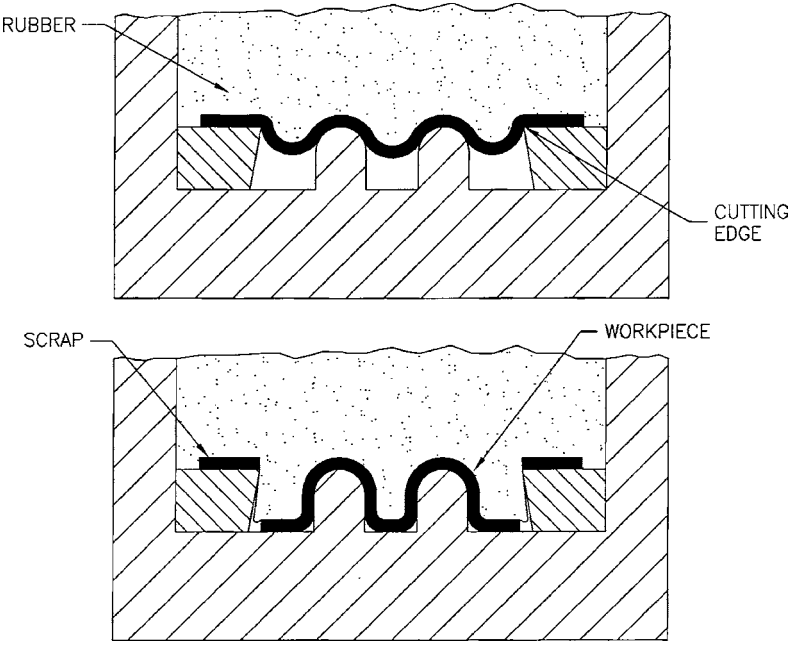

FIGURE 8-32 Complicated forming and trimming, flexible tooling.

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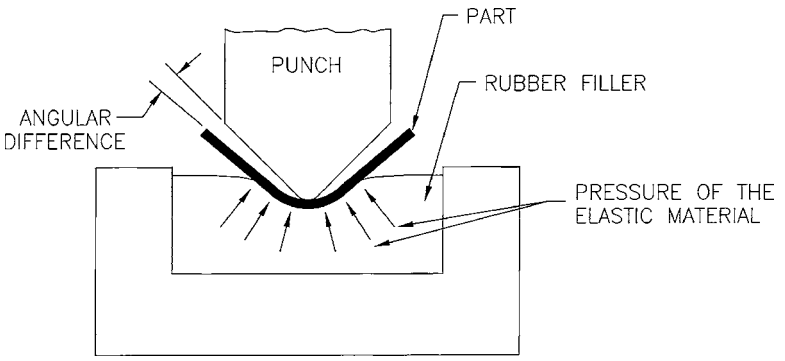

FIGURE 8-33 V-bending with elastic tooling.

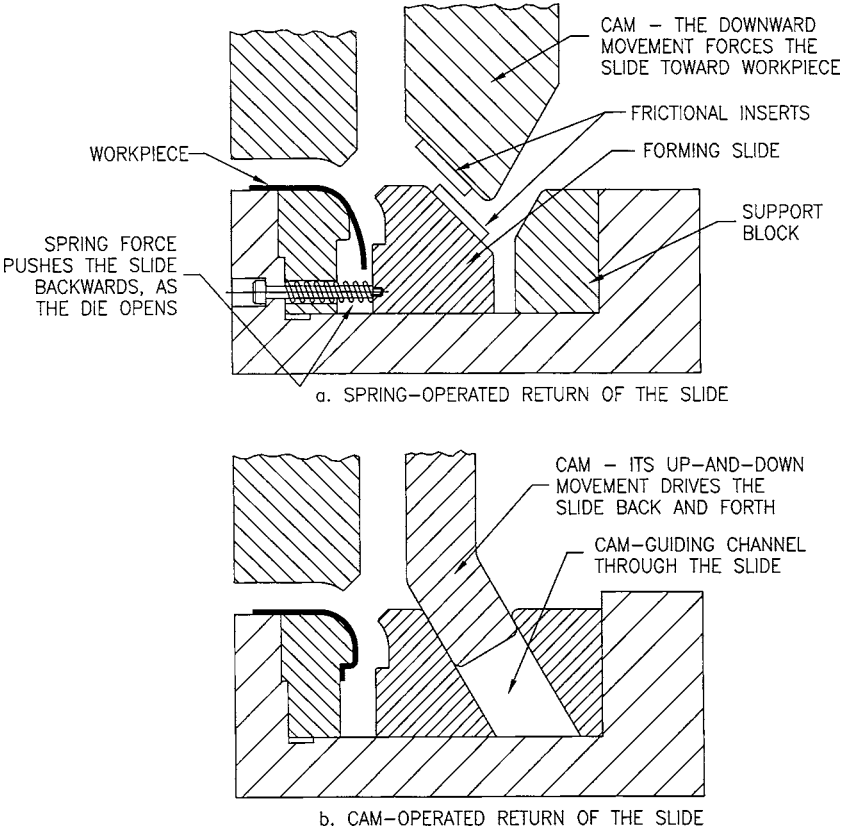
CAM – THE DOWNWARD MOVEMENT FORCES THE SLIDE TOWARD WORKPIECE
FRICTIONAL INSERTS
FORMING SLIDE
WORKPIECE
SUPPORT BLOCK
SPRING FORCE PUSHES THE SLIDE BACKWARDS, AS THE DIE OPENS
a. SPRING–OPERATED RETURN OF THE SLIDE
CAM – ITS UP–AND–DOWN MOVEMENT DRIVES THE SLIDE BACK AND FORTH
CAM–GUIDING CHANNEL THROUGH THE SLIDE
b. CAM–OPERATED RETURN OF THE SLIDE

FIGURE 8-34 Two types of cam movement.

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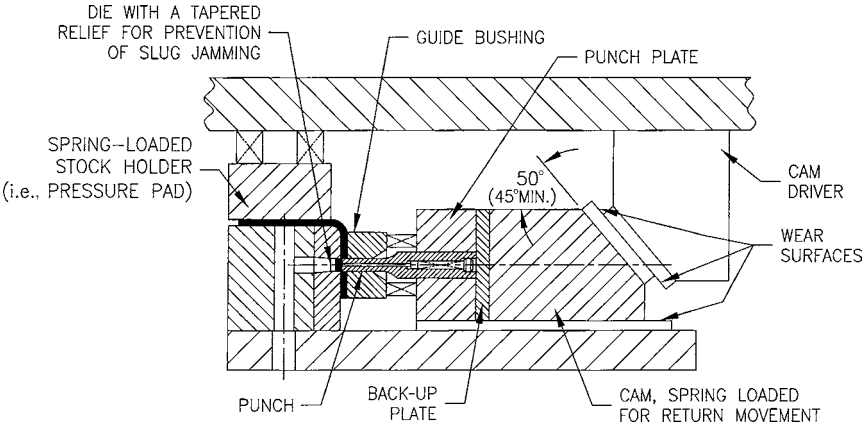

FIGURE 8-35 Side-piercing cam arrangement.

bushing, which is spring-loaded to retain the pierced part during the retrieval of the punch. The punch is equipped with a spring-loaded central pin for a positive ejection of the slug. The whole punch assembly is tied together and it is returned into its original location via spring force on retrieval of the cam driver.

The opening for slug removal may need to be inclined in some cases, while a straight hole will suffice in other situations. The surfaces of the slug-removing path should be flame hardened for greater resistance to damage.

8-6-6-1 Cam With a Dwell. Cam with a dwell is sometimes used to prolong the forming operation, or where additional procedures are to follow and a time for their accomplishment is needed (Fig. 8-36). This type of a cam can be implemented in cases where its path of travel does not need any further adjustment.

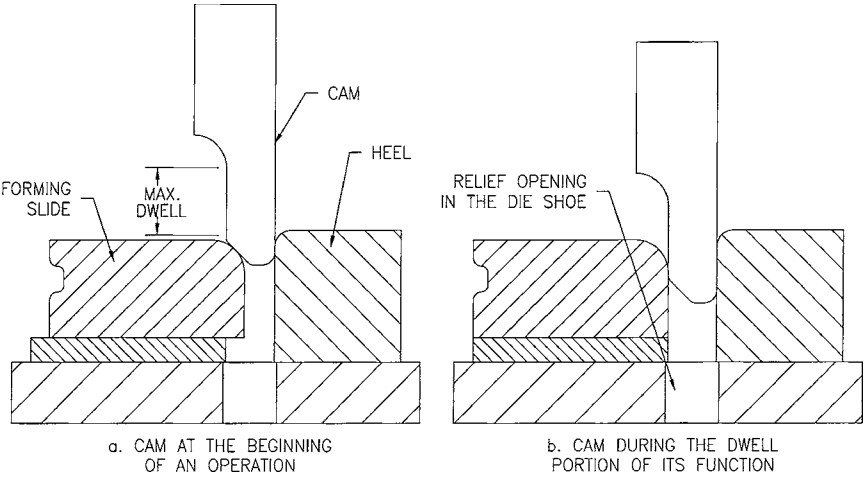

FIGURE 8-36 Cam with a dwell.

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During the dwell period of the cam function, the slide is remaining pushed against the formed part motionless, even though the press ram is still descending. Care must be taken when calculating the height of the assembly, so that a wider shank of the cam does not hit the slide. The tip of the cam should not come into a contact with the die shoe either, and where a questionable situation exists, a relief opening in the shoe must be provided.

Movement-wise, a calculation of the actual movement of the slide with a provision for variation in the stock thickness must be performed. It is often advisable to provide a larger-than-required gap for the formed material in order to account for all its differences in thickness. Fine-tuning of the distance traveled can be accomplished by shimming the assembly where appropriate.

8-6-6-2 Miscellaneous Cams. Standardized cam units can now be purchased for various uses. As a sample, an aerial cam slide unit is shown in Fig. 8-37, and a die-mount cam slide is in Fig. 8-38. These cam assemblies have soft mounting surfaces for standard or custom applications, plus hardened, self-lubricating wear plates. Standard angles are available in the range from 25° through 50° and special angles can be ordered upon request.

A slide movement producing a curl is shown in Fig. 8-39. Here the material to be formed is nested in the die block, where it is further secured in its position by the approaching slide. When the exposed edge of material encounters the beginning of a radius in the slide, it starts to follow its shape, forming a curl.

The location of a burr on the sheet-metal material is of importance in this process, as it should always be positioned away from the forming surface of the tooling. Flipping the burr to face the slide may obstruct the curling action and produce deformation of the part instead. In some cases, it may also scratch the surface of the tool's curling section.

8-6-7 Bending of Miscellaneous Materials

Various bending calculations that do not fit into any described category are presented here for possible evaluation and use. They have proved quite accurate for certain materials and applications.

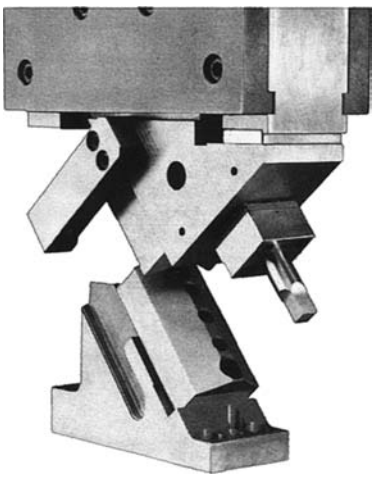

FIGURE 8-37 Aerial cam slide unit. (*Reprinted with permission from Danly IEM, Cleveland, OH.*)

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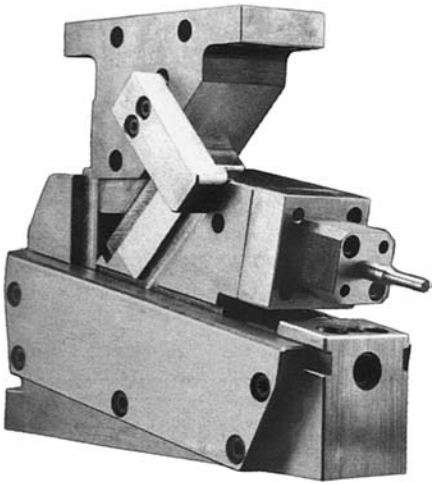

FIGURE 8-38 Die-mount cam slide unit. (*Reprinted with permission from Danly IEM, Cleveland, OH.*)

1. *Bending of soft copper and soft brass.* The formula to calculate bend allowance is Eq. (8-10). Its application is the same as previously described.

$$BA_{Cu} = CR_{in} + (0.55t) \tag{8-10}$$

where R_{in} = inside radius of the bend
t = material thickness
C = constant, depending on the angle of the bend. For 90° bends, this value is 1.5708. For bends of different angularity, see Table 8-7.

Further calculation of the total length of the part L_{total} is performed the same way, as shown in Eqs. (8-5*a*) or (8-5*b*).

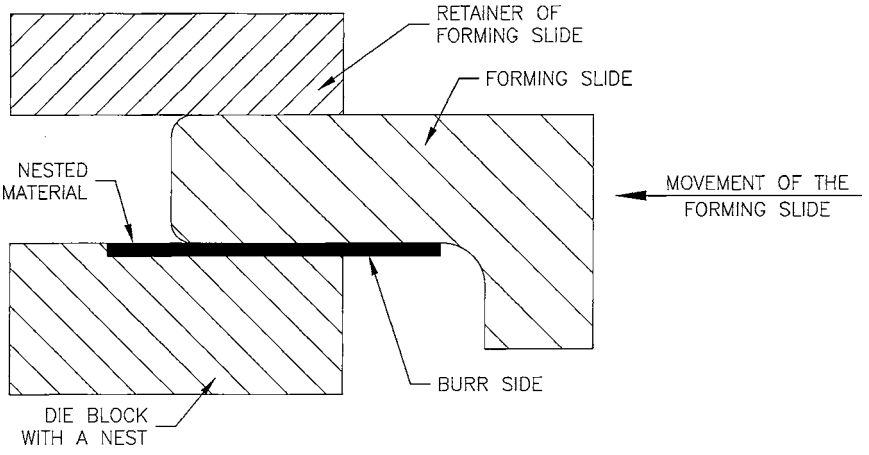

FIGURE 8-39 Curling cam operation.

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2. *Bending of half-hard copper, half-hard brass, and half-hard steel.* The formula to obtain the bend allowance is

$$BA_{1/2\text{Cu}} = CR_{\text{in}} + (0.64t) \tag{8-11}$$

To calculate the total length, use the bend allowance obtained this way in Eqs. (8-5*a*) or (8-5*b*).

3. *Bending of hard copper, bronze, cold-rolled steel, and spring steel.* The bend allowance formula is

$$BA_{\text{spring}} = CR_{\text{in}} + (0.71t) \tag{8-12}$$

Use Eqs. (8-5*a*) or (8-5*b*) to calculate the total length of the part.

8-7 SPRINGBACK

Springback is the amount of elastic distortion a matrial has to go through before it becomes permanently deformed, or formed. It is the amount of elastic tolerance, which is to some extent present in every material, be it a ductile, annealed metal or a hard-strength maraging steel. In ductile materials, the springback is much lower than in hard metals, with dependence on the modulus of elasticity (also called *Young Modulus*) of a particular material. The amount of springback increases with greater yield strength or with the material's strain-hardening tendency. Cold working and heat treatment both increase the amount of springback in the material. Comparably, the springback of low-strength steel material will be smaller than that of high-strength steel and springback of aluminum will be two or three times higher yet.

Springback occurs in all formed or bent-up parts on release of forming pressure and withdrawal of the punch. The material, previously held in a predetermined arrangement by the influence of these two elements, is suddenly free from outside restrictions and immediately makes an attempt to return to its original shape and form. (Fig. 8-40).

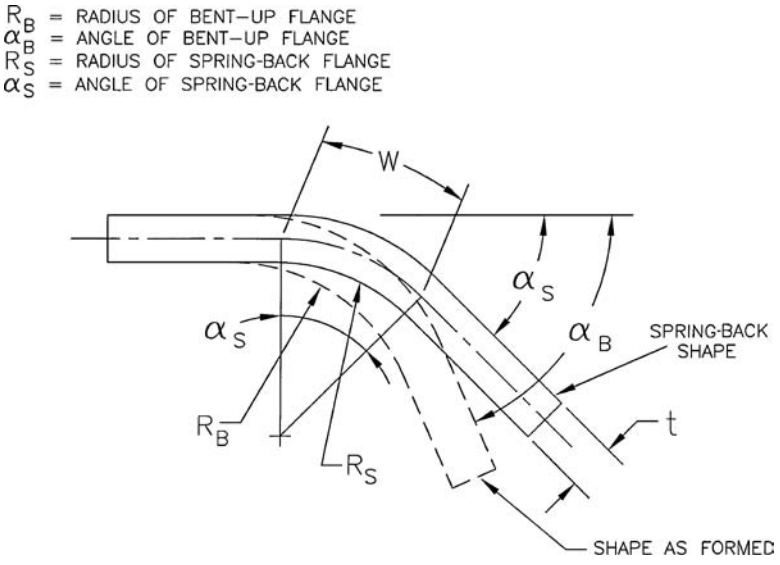

FIGURE 8-40 Springback.

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The angle of the bent-up flange α_B is greater than that altered by springback α_S. The same way, the radius R_B increases on becoming affected by the springback R_S. However, the lengthwise portion W, which is the length of the arc, remains the same. Its relationship to other areas of significance is given as

$$W = \alpha_B\left(R_B + \frac{t}{2}\right) = \alpha_S\left(R_S + \frac{t}{2}\right) \tag{8-13}$$

From this relationship, a spring-back factor K can be obtained:

$$K = \frac{R_B + \frac{t}{2}}{R_S + \frac{t}{2}} \tag{8-14}$$

Usually springback can be found between 0.9 and 1.0 for bends, using small bend radii.

Equation (8-14) was proved true for bends with large bend radii or for those with small bend angles. However, with small bend radii, it may be considered valid only if the bend angle has a greater than 45° bending angle. For small bending angles and sharp bend radii, the spring back is usually quite large.

Values of spring back for steel are shown in Table 8-8.

Shown in Fig. 8-41, the yield stress of material is exceeded at a certain point, at which moment the whole deformation so far attained is elastic, or a springback. Should we release the pressure at that moment, the material will return to its normal shape.

However, we continue to exceed the material's elastic limitations, as we arrive at a point "A." A line parallel to the material forming line can be drawn from this point and its horizontal difference from the point "A" is the value of springback. Additional forming causes the material to become work-hardened, which moves us to the point "B." Here, the material's springback is greater, enhanced by work hardening qualities of the steel.

The slope of the material's forming line is dependent on the Young modulus. It is therefore pertinent to always specify the steel (or any material for that purpose) to be ordered within the same yield strength range. A difference in yield strength will definitely produce variations in forming, in work hardening, and in the final outcome of metal stamping process.

TABLE 8-8 Springback Values for Steel Material

Angle of the bend	Condition of material	Ratio R/t				
		1	2	4	6	10
30°	Annealed	1	1	3	4	7
30°	Hard	0	2	5	8	14
60°	Annealed	0	1	2	3	5
60°	Hard	0	1	3	5	8
90°	Annealed	0	0	1	2	4
90°	Hard	−1	0	2	3	7
120°	Annealed	−1	0	0	1	3
120°	Hard	−1	0	1	2	4

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BENDING AND FORMING OPERATIONS

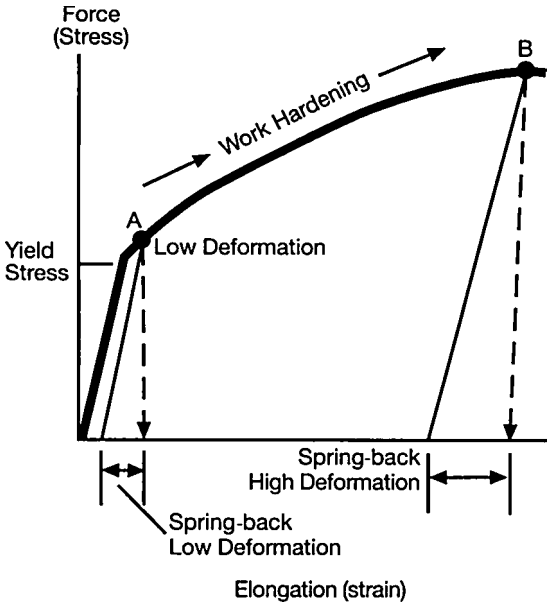

FIGURE 8-41 Force-elongation diagram showing the effects of work hardening and springback. (*From: MetalForming Magazine®, January 1999, by Stuart Keeler. Reprinted with permission from PMA Services, Inc., Independence, OH.*)

8-7-1 Springback Removal

There are several methods of springback removal in bending, most of them utilizing either overbending or coining. In Fig. 8-42, the formed part's sides are secured in their location after forming by a punch or die section, which most often coins the material. The bending method shown in Fig. 8-42*a* counts on the die's curved bottom to return the formed part to its flat position on retrieval of the bending forces. This will also force the sides toward the center, eliminating the springback effect. In Fig. 8-9 shown previously, a method utilizing ironing action against the bent up sides of the part is depicted.

Selective coining of material can be used for other purposes as well (see Fig. 8-43). For example, by strategically coining strips of bent-up U-shapes, a bow, (i.e., camber) and perhaps twist as well, can be removed from the material. The effect of the coining process is that of interruption of the flow of stress lines that would normally be present there, a residue from bending operation.

Bending of U-channel shapes presents more problems, though. Another often-encountered flaw is the emergence of vacuum, which may develop during the downstroke of the press. At that moment, the material is fully retained between the forming punch and die and may sticks either to the punch, or the die, in the latter case being difficult to eject. Coating of critical surfaces, relieving some areas of contact, bending in two strokes, or increasing the spring pressure—none of this can help where vacuum tends to develop. Air holes through the tooling, punch, die, and the spring pad, are still the best solution to this problem.

Production of large radiused (shallow) bends is yet another area of problems waiting to be solved. Large radiused bends tend to spring back enormously, and are absolutely

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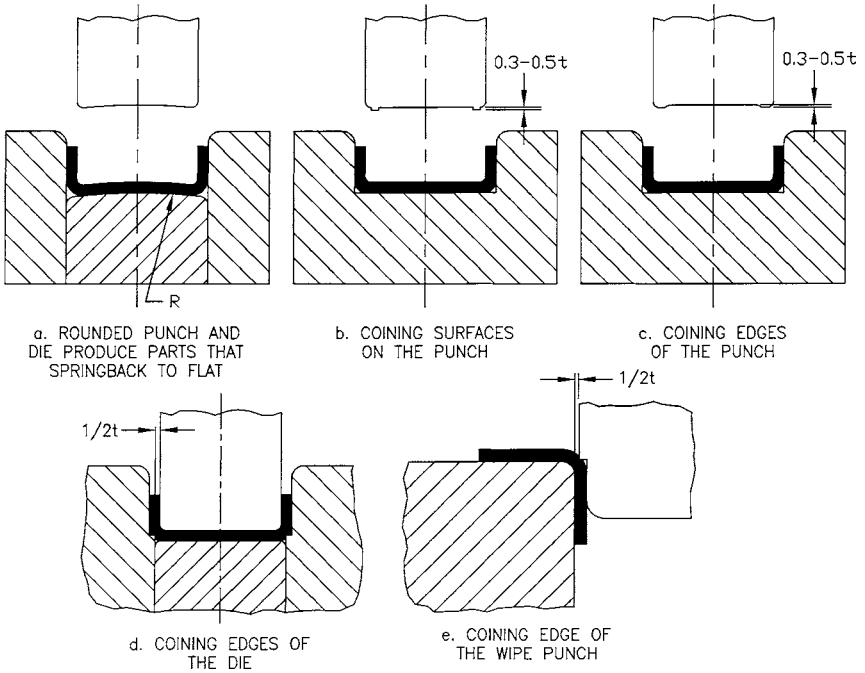
0.3–0.5t
0.3–0.5t
R
a. ROUNDED PUNCH AND DIE PRODUCE PARTS THAT SPRINGBACK TO FLAT
b. COINING SURFACES ON THE PUNCH
c. COINING EDGES OF THE PUNCH
1/2t
1/2t
d. COINING EDGES OF THE DIE
e. COINING EDGE OF THE WIPE PUNCH

FIGURE 8-42 Methods of springback control in bending. (Pictures *d* and *e* are from: *Practical Aids For Experienced Die Engineer, Die Designer, and Die Maker 1980. Reprinted with permission from Arntech Publishers, Jeffersontown, KY.*)

unpredictable when it comes to their shape retention, especially where large segments and softer materials are used.

Several preventive methods can possibly be used, some of them shown in Fig. 8-44. Here the shallow form has its sections ironed right after the bend radius, to secure the bend formation. The upper flanges are slanted, and additionally, the bottom of the part can be coined for further security of the shape. Not always are all these remedies needed, but a combination of some may often be found beneficial.

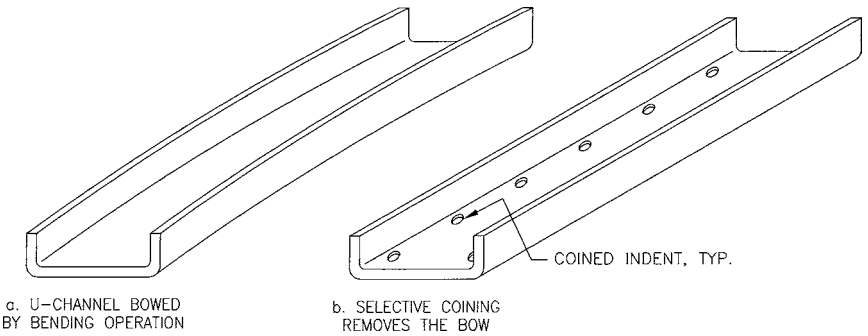

FIGURE 8-43 Coining for removal of stresses in strips.

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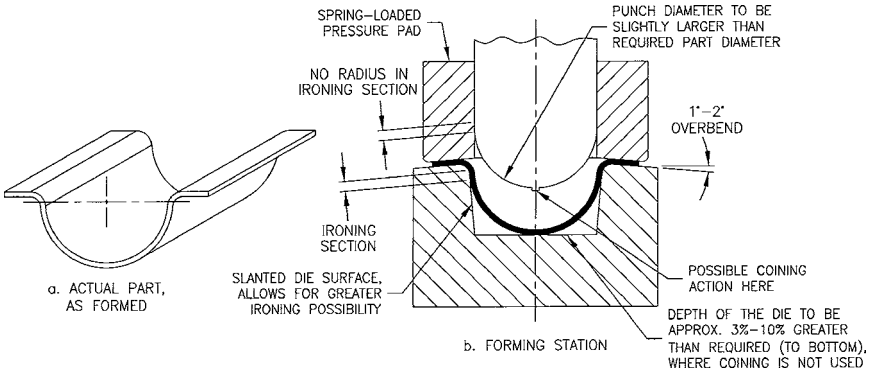
SPRING–LOADED PRESSURE PAD
PUNCH DIAMETER TO BE SLIGHTLY LARGER THAN REQUIRED PART DIAMETER
NO RADIUS IN IRONING SECTION
1°–2° OVERBEND
IRONING SECTION
a. ACTUAL PART, AS FORMED
SLANTED DIE SURFACE, ALLOWS FOR GREATER IRONING POSSIBILITY
POSSIBLE COINING ACTION HERE
DEPTH OF THE DIE TO BE APPROX. 3%–10% GREATER THAN REQUIRED (TO BOTTOM), WHERE COINING IS NOT USED
b. FORMING STATION

FIGURE 8-44 Springback control in a shallow-radiused part.

8-7-2 Residual Stresses

As already mentioned elsewhere in this publication, every forming operation consists of two types of deformation: elastic deformation and plastic. Where the plastic deformation produces permanent changes in the part, that is bending, forming, and drawing, the influence of elastic deformation is but temporary. On cessation of forming force, it allows the formed segment to almost completely negate its effect and return back to its preelastic shape and location. This is a springback.

Yet, there is a portion of elastic deformation that cannot be totally released this way and which remains trapped within the material. These small pockets of elastic stresses are called residual stresses and they can be found throughout the part's geometry, locked in by the changes due to plastic deformation. Evenly distributed residual stresses may cause but a slight dimensional distortion of the part. However, if unevenly dispersed and acting in different directions, these stresses can produce warping, twisting, oilcan, and other defects.

It may sometimes happen, as a part is formed, that it comes out of the die almost perfect. But an additional operation, be it piercing, trimming, additional forming, restriking, or welding, may suddenly produce an unexpected amount of distortion and the previously perfect part ends up in a scrap bin. This is due to residual stresses, introduced into the material during its fabrication.

In welding, the immediate vicinity of the weld becomes stress relieved. This in itself can have a profound effect on the part either immediately or later in service. Then, due to cyclic loading, all defects tend to become emphasized with time and may cause the part's collapse and perhaps total destruction.

Both residual stresses and springback can bring about a host of unexpected problems and a sound part design, along with a good tool design, combined with a good manufacturing practice cannot be overemphasized. There are certain features encountered in sheet-metal parts that almost always produce greater than necessary stresses in formed parts. Such features consist mainly of sharp corners, sharp bend radii, greater differences in height, to name but a few.

8-8 SURFACE FLATNESS AFTER BENDING

In bending, as in drawing, it is sometimes quite difficult to produce a flat surface on a part. Especially with larger flat areas, these can easily become warped, bowed, inclined,

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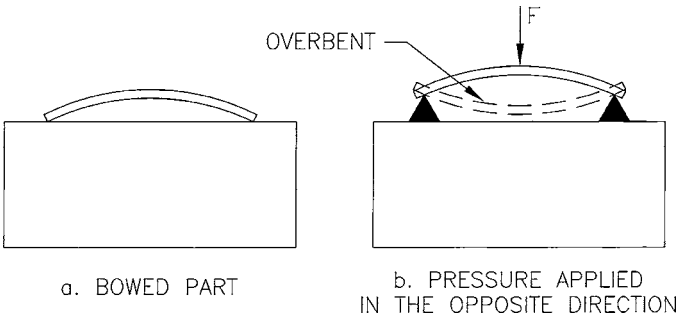

FIGURE 8-45 Straightening of sheet metal.

or otherwise distorted, but not flat. Such a surface, when pressed upon by hand, snaps back and forth, like an oilcan, from which this occurrence took its name: an *oilcan effect.*

In order to prevent this from happening, ribs, joggles, and other strengthening indentations were introduced, to provide for the dimensional as well as functional stability of parts. Objects that have to stand on a flat surface, like containers or cans, have their bottoms either bent or drawn in, keeping but a narrow rim of flat surface to stand on. Some products have their contact surfaces offset, with a small ridge to provide for the necessary flatness.

Where the supposedly flat surface of an object is distorted or warped, no amount of hammering or presswork will make it straight again. This is due to the mechanical properties of the material, which does not allow for any permanent alteration unless the elastic limit of the material is exceeded.

Part a in Fig. 8-45 cannot be straightened by any feasible amount of pressure applied from above. In order to flatten this surface, it must be reversed and supported on two extreme ends, as shown in part b. In such a position, even a minute force will produce the flattening effect.

Another way known, a part such as this can be straightened, is when submitted to pressures excessive of its modulus of elasticity. Using hydraulically produced forces these methods are sometimes resorted to, lately. Of course, the cost of the necessary equipment can bring this solution out of reach of most manufacturers.

Annealing of the part may be found of help sometimes, provided there are no excessive residual stresses within its structure. If such is the case and residual stresses will become relieved by the annealing process, severe distortion may result. Localized annealing by a torch was usually not found effective.

Often, where parts cannot be formed to hold their shape, a double bending method or reverse forming is used (Fig. 8-46). In such a case, the bend is first produced in the opposite direction to that which is desired. The bend is then reversed until a correctly shaped product is obtained.

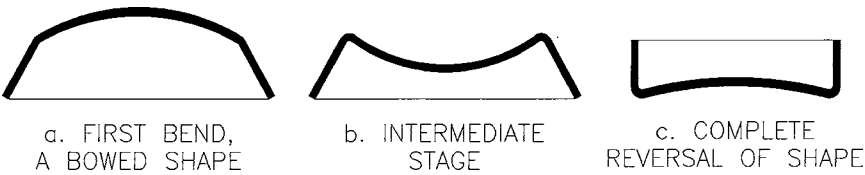

FIGURE 8-46 Method of bending and rebending for accuracy.

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BENDING AND FORMING OPERATIONS

As can be expected, not all materials can handle such a rough treatment the reversed bending presents. This operation introduces a massive amount of strain into the formed section (i.e., mainly the corners). This may not only weaken these areas; it will also cause a greater than ordinary work hardening of the same. Tearing of the metal, wrinkling, and other defects may result.

8-9 FORMING

Metal forming is a process totally dependent on the influence of outside tensile forces against the structure of the material. The resulting permanent deformation is called *forming*. The force-exerting instrument is the punch, which by pulling the sheet-metal material along, makes it enter the die, where it is compelled to take upon itself the impression of the assembly.

The decision if the part is to be formed or drawn is usually based on the evaluation of its shape and dimensional requirements. Drawing is utilized for those parts made of thicker materials or for those with vertical (or slightly inclined) walls and sharp corners at the bottom.

Since a forming die may often be instrumental in the formation of wrinkles or cause development of excessive tensile strains in the material, which away tear the part in the process, drawing is often resorted to in such cases.

8-9-1 Forming of Singular Recesses

Singular recesses in the flat metal sheet are usually formed by stretching or drawing. Stretching is reserved for parts with smooth connection of contours, without excessively sharp edges. Several samples of stretched parts are shown in Fig. 8-47.

The maximum amount of stretch for a given material depends on its distribution over the area of stretch. Naturally, the larger such an area is, the greater the maximum amount of stretch that can be obtained.

To evaluate the strain with respect to the amount of stretch, Eq. (8-15) may be used:

$$s = \frac{L_s - L_o}{L_o} \tag{8-15}$$

where s = stretch

All other values are in Fig. 8-48.

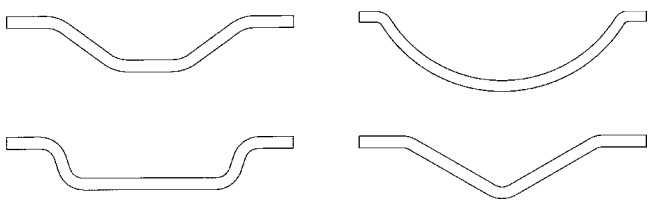

FIGURE 8-47 Shapes of stretched parts.

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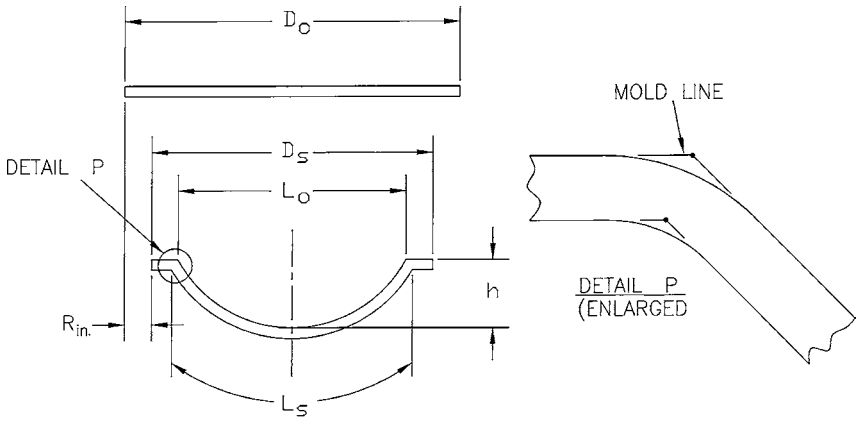

FIGURE 8-48 Dimensional values of a stretched recess.

The linear distance of the drawn-in portion of the radius R_{in} can be calculated:

$$R_{in} = \frac{1}{2}(D_o - D_s) \tag{8-16}$$

All calculations or measurements should be taken between mold lines, ignoring the radii of the edges. The mold line, as shown in Fig. 8-48, is an extension of the curved or linear portion, connecting with another line sharply, with no radius applied (see detail "P").

Round recesses can be assessed from Table 8-9. Their stretch values are based on the ratio of the depth h to the length of the recess in flat L_s.

8-9-2 Stretch Flange Forming

Stretch flanges, when viewed from the top, form a concave curvature. These are flanges which on forming must be lengthened or stretched (Fig. 8-49). They may be compared to flanges surrounding a hole in sheet metal. Processes such as extruding, dimpling, and countersinking are all basically stretch flange forming.

TABLE 8-9 Stretch Values of Circular Recesses

Ratio L_s/L_o	Ratio h/L_o	Stretch %
1.05	0.157	5
1.10	0.218	10
1.15	0.264	15
1.20	0.302	20
1.25	0.334	25
1.30	0.361	30
1.35	0.386	35
1.40	0.408	40
1.45	0.429	45
1.50	0.447	50

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BENDING AND FORMING OPERATIONS

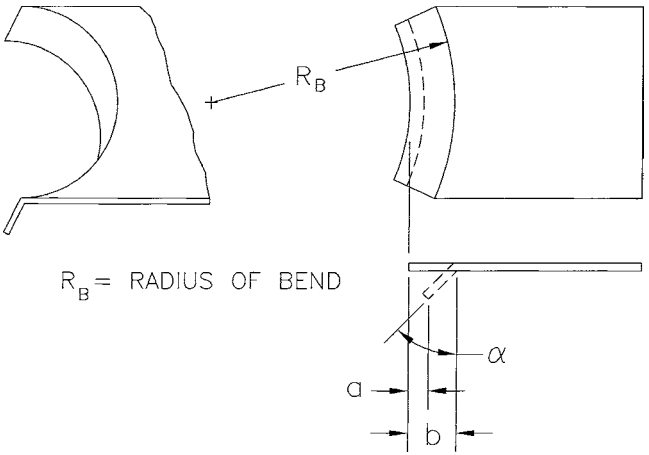

FIGURE 8-49 Stretch flange.

The evaluation of the flange type should be pursued by observing the flat layout of a part, which clearly shows where the material for each flange may be taken from.

Owing to their stretching, the material thickness of stretch flanges decreases. This places a lateral strain on the material, with a resulting circumferential tension. The strain S_e can be calculated from the ratio of the wall thickness Δt and the amount of wall thickness change t as follows:

$$\frac{\Delta t}{t} = -\frac{e}{2} \tag{8-17}$$

A minus sign attached to Eq. (8-17) depicts the variation in wall thickness, which in stretch flanges diminishes (−) and in shrink flanges increases (+).

From this relationship, other values may be assessed with the use of the formula

$$e = \frac{a}{R_B - b} \tag{8-18}$$

where all values are as shown in Fig. 8-50.

However, with the bend radius being too small, the value a of flange movement may be approximated. In such a case, the material thickness is to be considered zero and the flange width constant. The formula to be used is then

$$a = b(1 - \cos\alpha) \tag{8-19}$$

Stretch flanges are limited by the amount of material from which they can draw for their development. Beyond such a limit, the flanges will crack around the edges and tear. Too small a radius of curvature also adds to the problems, and it should be made as generous as possible, with a definite preference for straight forming lines.

The limits on the 90° flange are as given by the equation

$$e_{\text{limit}} = 1 - \frac{\cos\alpha}{R_B/b - 1} \tag{8-20}$$

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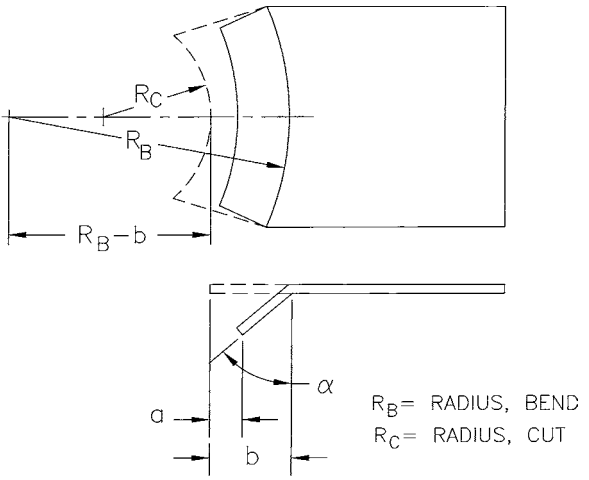

FIGURE 8-50 Stretch flange geometry.

8-9-3 Shrink Flange Forming

Shrink flanges are those which are reduced in length on forming, or shrunk. The shrunk flange, when viewed from the top, usually forms a convex line. The wall thickness of these flanges increases, which is caused by a circumferential compression during the forming process.

The lateral strain, acting within the flange material, can be calculated by using Eq. (8-17). Similarly as with the stretch flanges, other pertinent values may be assessed:

$$e = -\frac{a}{R_B + b} \tag{8-21}$$

where the values are as shown in Figs. 8-50 and 8-51.

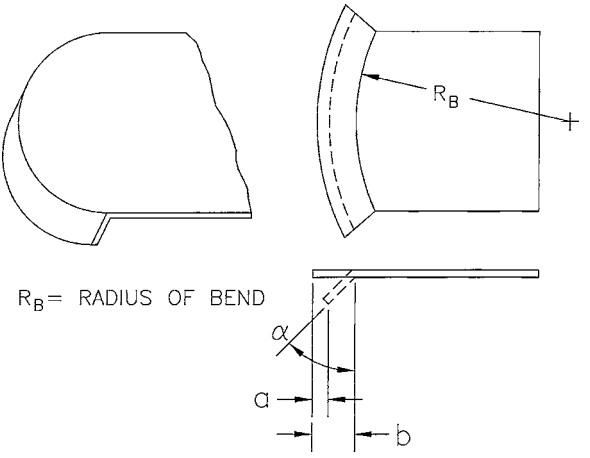

FIGURE 8-51 Shrink flange and its geometry.

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BENDING AND FORMING OPERATIONS

And again, the value a of flange movement may be approximated, using Eq. (8-19).

Shrink flanges are actually quite difficult to form from a flat blank. The material is often reluctant to succumb to such compressive stresses and has a tendency to wrinkle or buckle. With wider flanges, the tendency to wrinkling is increased.

Buckling is found controllable where the ratio of the flange width to the material thickness remains within a range of 3 to 4.

8-10 BENDING AND FORMING PRESSURE CALCULATIONS

Several formulas are utilized for calculation of bending and forming pressures. They may vary with the type of bending utilized.

1. *Bending in a V-die, with rectangular cross-section:*

$$P_V = \frac{k_V S W t^2}{L} \tag{8-22}$$

where k_V = die opening factor, 0.75 to 2.5 (larger values are for smaller R/t ratios and vice versa). A 1.33 value is used for a die opening of 8 times metal thickness.
W = width of the bent-up portion
L = distance between material supports (see Fig. 8-52)
S = ultimate tensile strength (Table 8-10)

2. *Bending in a U-die, equipped with a spring-loaded pressure pad:*

$$P_U = \frac{k_U S W t^2}{R_E + R_D + t} + P_{\text{pad}} \tag{8-23}$$

where k_U = die opening factor, 0.4 to 10
R_E = radius, die edge (see Fig. 8-53)
R_D = radius, bottom of U channel
P_{pad} = pressure of spring-loaded support

TABLE 8-10 Ultimate Tensile Strength of Materials

	Tons/In.^{2}	MPa [N/mm^2]
Steel, low carbon, 1025	30–51.5	410–710
Steel, medium carbon, 1045	40–91	550–1,250
Steel, high carbon, 1095	45–106.5	620–1,470
Steel, stainless, 303	42.5–62.5	585–860
Aluminum alloy, cold worked	6.0–31.5	80–435
Aluminum alloy, heat treated	11.0–41.5	150–570
Copper	16–28.5	220–390
Phosphor bronze	20–64	275–880
Zinc	9.75–15.5	135–215

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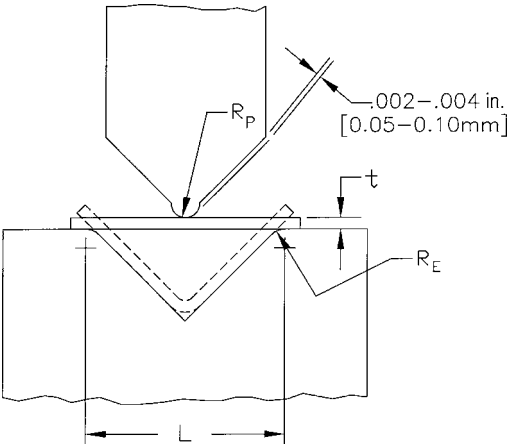

FIGURE 8-52 V-die bending geometry.

3. *Bending with bottoming (coining):*

$$P_{\text{bottom}} = (2 \text{ to } 4)P = Ap \tag{8-24}$$

where P = bending pressure of the particular process
A = area of part, subjected to coining
p = bending pressure (see Table 8-11)

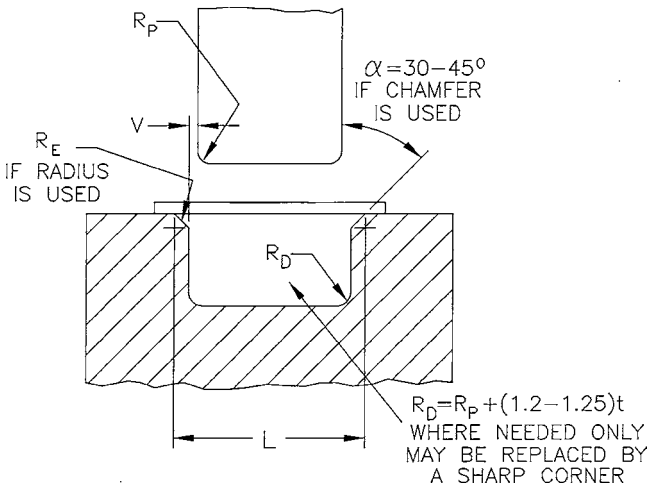

FIGURE 8-53 U-die bending geometry.

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TABLE 8-11 Approximate Bending Pressures

	Tons/in.^{2} Material thickness, in.		kPa Material thickness, mm	
	Under 0.125	0.125–0.375	Under 3	3–10
Steel, annealed	29–36	36–43	0.4–0.5	0.5–0.6
Steel, hard	36–43	43–58	0.5–0.6	0.6–0.8
Aluminum	7–15	15–22	0.1–0.2	0.2–0.3
Brass	22–36	36–43	0.3–0.4	0.4–0.5

Source: Svatopluk Černoch, *Strojně technická příručka*, 1977. Reprinted with permission from SNTL Publishers, Prague, CZ.

4. *Wipe bending dies' pressure calculation:*

$$P_{\text{total-wipe}} = \frac{SWt^2}{L} \tag{8-25}$$

where L = distance between supports of the material (see Fig. 8-54)
W = width of the bent-up portion
S = ultimate tensile strength (Table 8-10)

Subsequently, each of the three forces acting upon the appropriate point in the assembly is one-third of the total force. These forces are: (1) force of blank holder; (2) bending force of the punch; (3) final bottoming force of the punch (see Fig. 8-54).

$$P_{1 \text{ or } 2 \text{ or } 3} = 0.333\frac{SWt^2}{L} \tag{8-26}$$

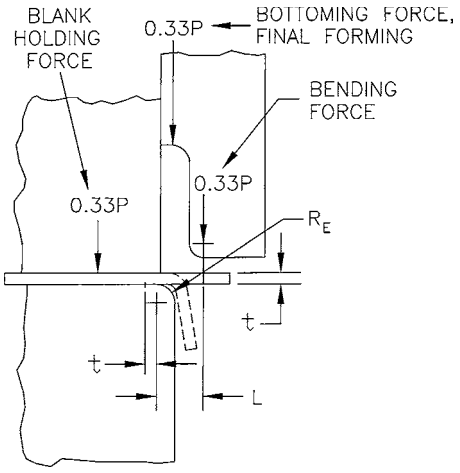

FIGURE 8-54 Wipe bending geometry.

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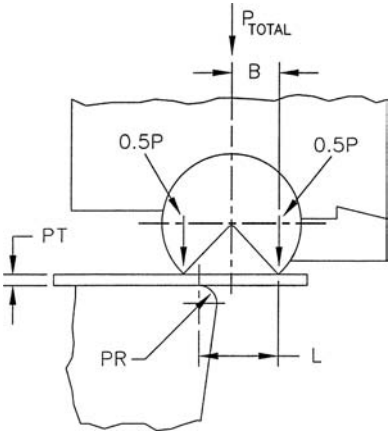

FIGURE 8-55 Rotary bending geometry. (*Reprinted with permission from Ready Technology, Inc., Dayton, OH. Patent Number 5,404,742.*)

5. *Calculation of the pressure involved in rotary bending is as follows*:

$$P_{\text{total}} = 2.25 S_{\text{T}} \frac{(PL)(PT)^2}{L} \tag{8-27}$$

where S_{T} = Tensile strength of the formed material
$L = PR + PT + B$

all other values per Fig. 8-55.

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CHAPTER 9
DRAWN PARTS

9-1 DRAWING OF SHEET METAL

Drawing is a technological process during which a flat piece of sheet-metal material (i.e., blank) is transformed into a hollow, three-dimensional object. Such transformation can be produced either in a single step, or in a sequence of operations, each of them changing the shape but partially.

During the process of drawing, the material is forced to follow the movement of a punch, which pulls it along, on its way through the die. There the shape of the part and sometimes even the thickness of it are altered.

At first, the drawn material has to overcome its own elastic limit, succumbing to plastic deformation right afterwards. Various forces are acting upon the drawn cup (as shown in Fig. 9-1), be it the blankholder's pressure, or the friction between the drawn shell and other components of tooling. The blank is sometimes restricted from unreservedly following the punch, by having its edges confined between the surface of the die and those of a blankholder.

The main area of concern on the drawn part is located between the heel of the vertical wall and the bottom of the shell, where, due to the change in flow direction, the vertical tension acting upon the material is transformed into a triple-axial tension. In this section, the material is being bent, while moving around the edge of the drawing punch, only to be straightened right afterwards, so that another successive segment can be bent-and-straightened. This is where the wall thickness can often become diminished on account of the length of the shell, which is being increased by the drawing process. Because of such drastic changes within material, this is where much cracking and tearing can be observed.

In drawing, the metal taken from the flange of the shell is used up to produce increase in height of the part. A rather crude demonstration of this shift is depicted in Fig. 9-2. Here the segments of material are being displaced, flowing away from the flange toward the body of the shell, pulled by the action of the drawing punch and drawing die.

The basic shape in drawing operation, the "blank," is but a flat piece of sheet-metal material of uniform thickness, most often round. From this shape, a shell can be drawn. Even though during the process of drawing the blank's shape changes, often along with its thickness, its volumnar value remains the same, should it be drawn into a short, thick-walled cylinder, or a tall, thin-walled shell (Fig. 9-3).

With regard to the thinning of the drawn shells' wall, the final products can be divided into two basic categories:

- Those having the wall of the same thickness as the blank (Fig. 9-4*a*)
- Those having the wall thickness diminished (Fig. 9-4*b*)

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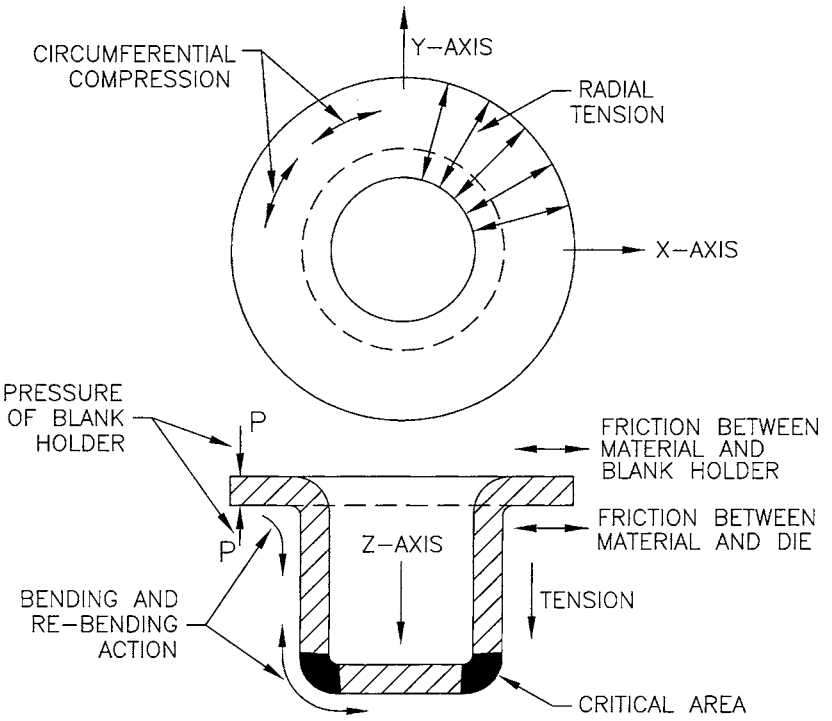

FIGURE 9-1 Forces involved in cup-drawing process.

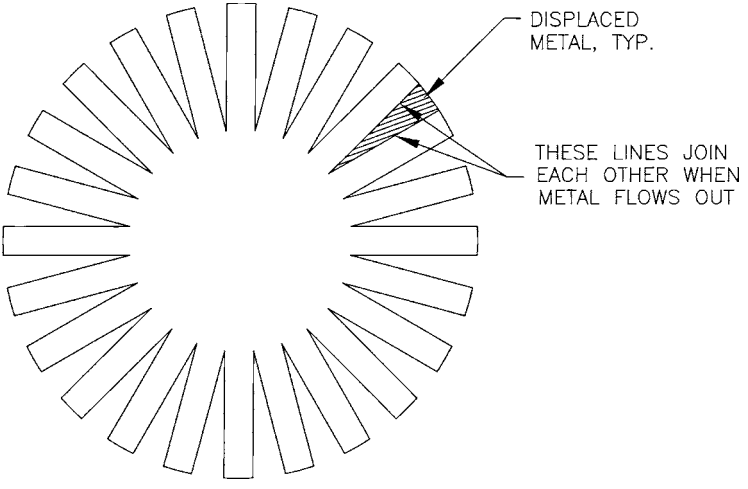

FIGURE 9-2 Displacement of metal in drawing.

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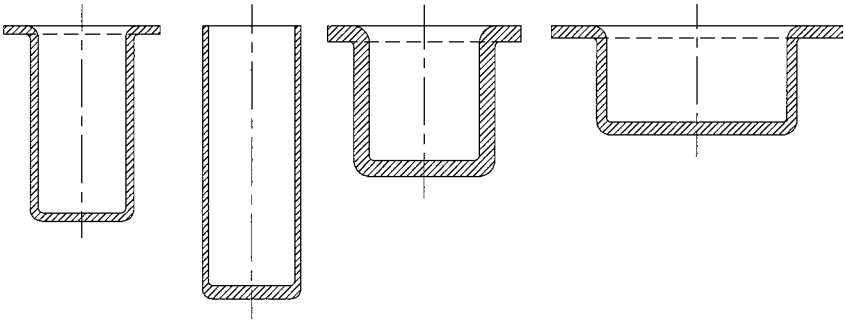

FIGURE 9-3 Volumnar equality of shells made from the same blank.

The size of the blank must be well assessed, to provide for all the needed amount of material and yet not be excessive in size or volume. Drawing from blanks the diameter of which is too small for their depth always poses a problem, as the thinning of the walls may be unreasonable and products may emerge from the die distorted or fractured.

Numerous other influences controlling the outcome of the drawing process can be found within mechanical properties of the material, such as strength, ductility, elasticity, and even thickness of the drawn stock. Should these values be either inadequate or excessive, they certainly will have an effect on the drawn part, and either favorably or negatively alter the whole process and its outcome.

The total expansion in depth often cannot be attained in a single operation. No material, with the exception of a rubber band, has such elastic properties as to allow for its stretching into depths greater than certain limiting percentages, which are listed later in this chapter. If a part is drawn more than it can tolerate, its stretching will place such a strain on its structure that a permanent deformation followed by fractures and tearing will result.

Therefore, drawing into greater depths must be done in stages, with each operation to be performed within the limits set for that particular material. And each drawing pass should stretch the shell slightly more until a final drawn cup is produced (Fig. 9-5).

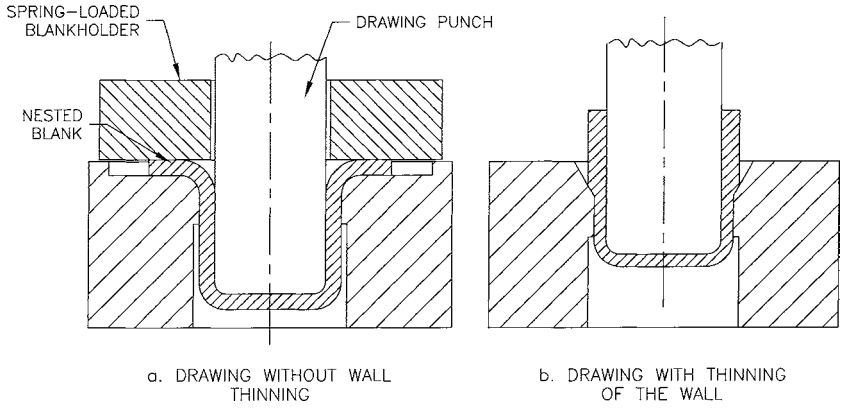

FIGURE 9-4 Two types of drawing operations.

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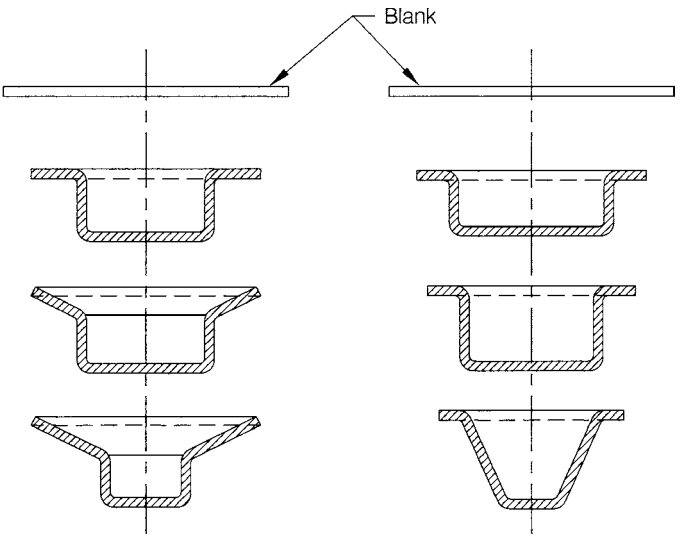

FIGURE 9-5 Sequence of drawing operations.

To produce a well-shaped and high-quality drawn part, the edges of both punch and die must be radiused, or chamfered; otherwise tearing of material will occur. The radii should be quite liberal, ranging at least four times the material thickness, even though the part's blueprint does not call for them. Where a drawn product must have smaller than possible radii, these should be produced later, in the restriking operation.

The restriking process does not draw the shape any further; rather, it forces the already drawn product to conform dimensionally to the requirements, unacquirable otherwise. During restrike, radii may be produced smaller than those enforced by the requirements of the drawing process. Bottoms may be flattened (somewhat), or bulged, or sides of a shell may be straightened (Fig. 9-6).

Restriking differs from redrawing in that the punch does not attempt to extend the drawn shell, whereas redrawing is used strictly for deepening of the drawn portion.

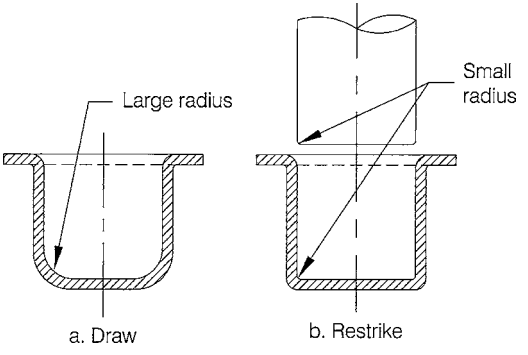

FIGURE 9-6 Restriking operation.

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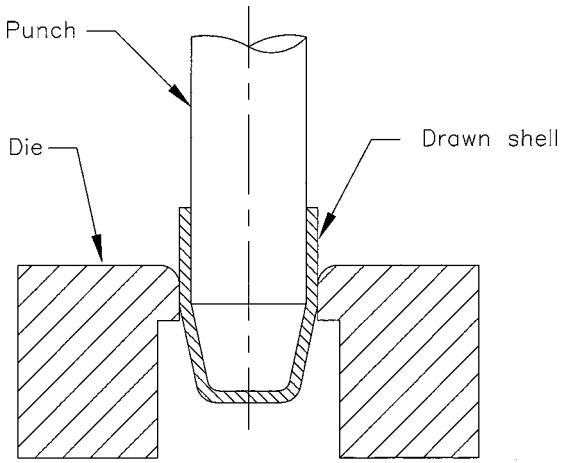

FIGURE 9-7 Drawn material conforms to the shape of the punch.

Repeated redrawing will produce strain hardening within the drawn material. After two or three drawing passes, some materials are hardened so greatly that the press force to overcome such an obstacle will have to be tremendous, and yet it may not achieve another extension in shape, as the hardened part may tear or rupture.

In such cases annealing of the drawn material must be performed in between. Annealing brings the mechanical properties of metal back to its predrawing stage, or at least quite close to it. Additional drawing passes may then be performed without causing unnecessary disturbances of the part's structure.

Some materials, such as brass, copper, and some steel, have to be annealed between every drawing stage. The effect of their strain hardening is too massive, handicapping further drawing operations. This may be observed with a piece of soft copper wire, which, when bent up and down several times in succession, suffers from such strain hardening that it becomes quite rigid.

Aluminum wire, on the other hand, softens and tears readily, with the breakage occurring within the area of the bend. When drawn, aluminum can attain deeper shapes in fewer drawing passes and with less annealing in between. Naturally, not all aluminum grades perform equally, which makes the above statement applicable mainly to alloys designated for drawing purposes.

Drawing differs from other metalworking processes in that it totally exploits the elastic and plastic properties of materials. The flat blank, forced to alter its shape to comply with the tooling, wraps around the punch, tightly adhering to its surface. Drawn parts always conform to the shape of the punch, while the opening in the die is immaterial, as long as its size is adequate for the given stock thickness (Fig. 9-7).

9-2 METAL MOVEMENT IN DRAWING OPERATION

During the process of sheet-metal drawing, the metal of the blank is exposed to various influences, which lead to its alteration in shape and sometimes in thickness (see Fig. 9-1). A plastic deformation of the material can be seen in the area, exposed to the pressure of the

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blankholder, while the plastic deformation caused by the drawing punch face is minimal. The plastic deformation occurring within the flange is positive where the radial tension is concerned, and negative owing to compression in the tangential direction. The direction of deformation normal to the flange is at first negative, with the resulting thinning of walls. But at the diametral distance greater than

$$\text{Punch dia.} + 1.214R$$

the deformation becomes positive, with subsequent increase in thickness (Fig. 9-8).

Plastic deformation of the material may be enhanced or decreased by altering the amount of friction between the drawn part and its tooling. However, the influence of friction varies with its location within the drawing process. Friction between the material and the drawing die or blankholder causes the radial tension and the ultimate coefficient of cupping to increase, with subsequent restriction of the maximum possible depth of draw. Friction between the material and drawing punch exerts an opposite influence on the outcome by increasing the maximum possible depth of the draw as a consequence of increase in friction.

This scenario may sometimes be enhanced by frictional inserts in the punch or by roughing of its cylindrical surface. The alteration is efficient even as a prevention of the excessive plastic deformation, or occurrence of wrinkles.

Wrinkling of material can also be prevented by the inclusion of a blankholder within the drawing die arrangement. The blankholder not only prevents wrinkling of the flange, it also retains the blank, so that it may not be pulled into the die without being drawn.

Not all materials need the blankholder, though. Some thicker stock may be successfully drawn without being retained under pressure. However, deforming influences within the flange may develop, caused by the tension σ, the value of which depends on the cupping strain factor E_c. Where such tension is greater than the critical tension σ_{crit}, which is dependent on the thickness of stock, a blankholder is necessary.

A cross-section of the drawn part is shown in Fig. 9-9. Here the thinning of various areas around the punch tip is exaggerated for clarity. The uneven upper surface is caused by differences in anisotropy of the material, which is explained in the next section.

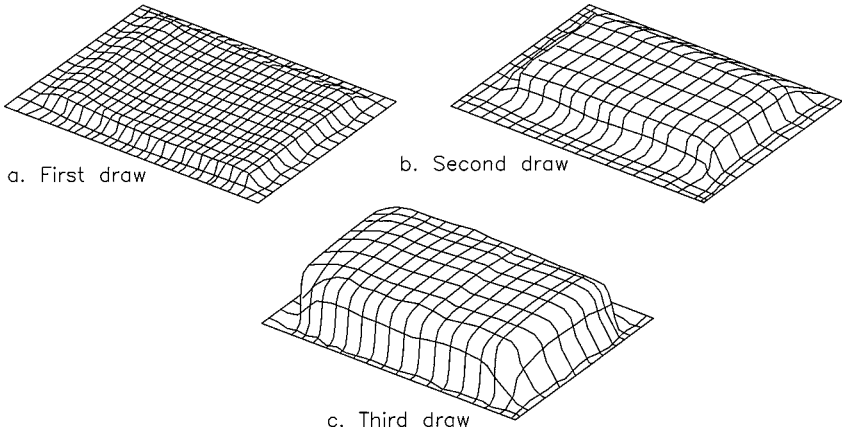

FIGURE 9-8 Structural changes during drawing operation.

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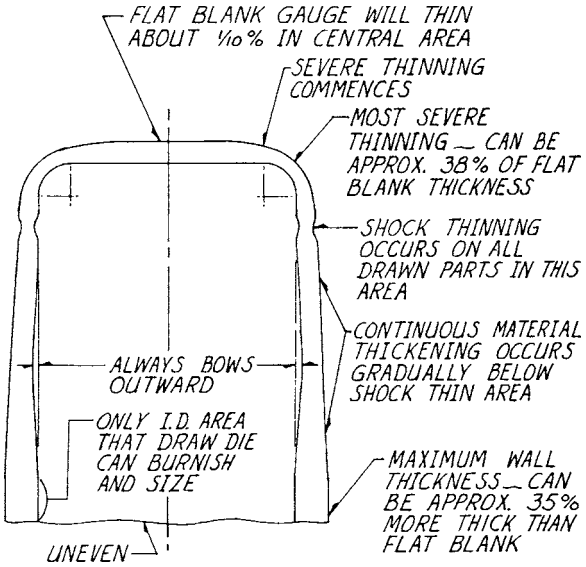
FLAT BLANK GAUGE WILL THIN ABOUT 1/10% IN CENTRAL AREA
SEVERE THINNING COMMENCES
MOST SEVERE THINNING — CAN BE APPROX. 38% OF FLAT BLANK THICKNESS
SHOCK THINNING OCCURS ON ALL DRAWN PARTS IN THIS AREA
CONTINUOUS MATERIAL THICKENING OCCURS GRADUALLY BELOW SHOCK THIN AREA
ALWAYS BOWS OUTWARD
ONLY I.D. AREA THAT DRAW DIE CAN BURNISH AND SIZE
MAXIMUM WALL THICKNESS — CAN BE APPROX. 35% MORE THICK THAN FLAT BLANK
UNEVEN

FIGURE 9-9 Cross section of the drawn shell. (*From: Practical Aids For Experienced Die Engineer, Die Designer, and Die Maker 1980. Reprinted with permission from Arntech Publishers, Jeffersontown, KY.*)

9-3 TECHNOLOGICAL ASPECTS OF DRAWING PROCESS

A drawn part is exposed to various technological influences, which affect every manufacturing process and its outcome. These are factors, including but not limited to the type of tooling, the type of manufacturing process, the amount of friction, speed of the process, temperature of the product and its tooling, and numerous other influences, exerting their control over the final product.

All these factors may affect the part and its manufacturing process either singularly or in a combination of two or more circumstances. For example, the drawing process itself will be affected by the amount of friction, which may give rise to the temperature of working surfaces, with subsequent wear of the tooling.

There are numerous small and large influences, all insidiously waiting to be omitted from the total assessment of the situation, so that they may manipulate the process unexpectedly and at the most inopportune moment. All these aspects have to be properly evaluated so that their span of control is limited in scope and in magnitude as well.

9-3-1 Suitability of Materials for Drawing

A valuable contribution to the successful drawing process is a properly selected drawing material. The choice is governed mainly by the material's drawability, or rather by the portion of it regarding the deformation and its distribution. The value of deformation should be within 25 to 75 percent of the value of drawability.

Drawability of metals can be defined as their capacity to assume the predetermined shape without suffering any loss of stability, without fracturing or being otherwise distorted by the drawing process.

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9-3-1-1 Drawability Theories and Testing. There are several theories on materials' drawability, all supported by a thorough testing. Erichsen's test was carried in accordance with PN/68/11-04400 (Polish Standard), where a punch ending with a ø20-mm ball was used. The resulting fracture occurrence was determined with 0.01-mm accuracy. Jovignot's test utilized a ø50-mm die with ø5-mm profile radius. The accuracy of these findings was also 0.01 mm. In the Swift test, a ø32-mm punch with a flat face was used. The Engelhardt-Gross test employed a ø20-mm punch against the ø52-mm blank. The Fukui test, using a conical cup, was performed with ø8- to 27-mm punches. Siebel-Pomp tested 80 × 80 mm samples with a central opening of ø12 mm.

Various testing methods established the drawability factor as a function of the mechanical makeup of the material, depending mainly on its strength, elastic/plastic properties, and chemical composition.

A certain lack of relationship between Erichsen's drawability index and the chemical composition of the material renders the influence of the latter meaningless. Tested materials ranged in the following values: 0.045 to 0.16 percent carbon, 0.24 to 0.48 percent manganese, 0.011 to 0.039 percent phosphorus, 0.005 to 0.03 percent sulfur.

Other findings proved the influence of phosphorus and manganese on drawability controversial. In these tests, the phosphorus content ranged between 0.01 and 0.025 percent, while manganese was included at 0.25 to 0.39 percent.

Still other tests found that the 0.015 to 0.025 percent of phosphorus was actually an improvement to drawability.

The most pronounced effect on the materials' drawability was considered normal anisotropic plasticity, where the actual tests fully confirmed previously obtained theoretical analyses. However, the lack of conformity between the theory and experiments in the case of strain-hardening influence on the drawability was too obvious.

Experimental findings also substantiated the difference in the drawability of materials of the same thickness, as based on the type of manufacturing process of the basic steel sample. Materials stabilized by aluminum were found to have their elastic limits approximately 5 percent greater than those stabilized by titanium, whereas the drawability of titanium-stabilized steel was found 7 percent greater than that of the aluminum-stabilized steel.

9-3-1-2 Normal Anisotropy. Suitability of drawing materials should also be evaluated on the basis of its coefficient of normal anisotropy r. This coefficient is a ratio of the actual deformation (or variation) within the metal to the variation in its thickness. The relationship can be defined as

$$r = \frac{\ln(b_0/b)}{\ln(t_0/t)} \tag{9-1}$$

where all values are as shown in Fig. 9-10.

Coefficient of normal anisotropy is a speculative value, comparing the behavior of the flange material with that in the drawn section and with that located under the face of the drawing punch. A proper development of tangential and radial deformations within the flange and an attainment of low amounts of deformation within the drawn section of the shell are vital to the success of the drawing process. With higher values of coefficient of normal anisotropy, the material's formability will be greater, producing deeper draws and lowering the cupping strain factor.

Since the coefficient of normal anisotropy r is grain orientation-dependent, its value is specified with respect to its variation from the grain line, which is considered at 0°. Subsequently, r_0 goes along the grain line, r_{45} at 45°, and r_{90} at 90° (see Fig. 9-11). The mean value of the normal coefficient of anisotropy can be obtained from the formula

$$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{9-2}$$

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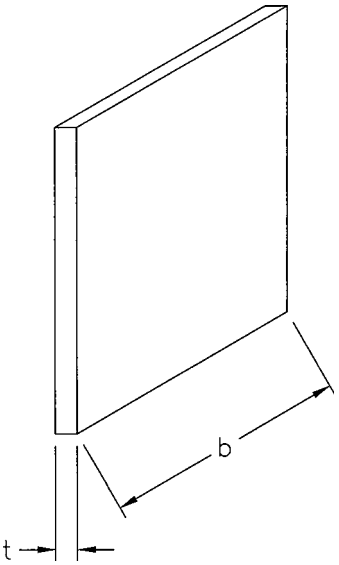

FIGURE 9-10 Values in normal anisotropy.

while the surficial anisotropy can be obtained with the formula

$$\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2} \tag{9-3}$$

The value of Δr influences the variation in drawing results with respect to the grain line of the material, which present themselves as a variation in straightness of the upper edge of the drawn shell, as shown in Fig. 9-12.

Where the anisotropy r would be greater in the direction of 0° and 90°, in that direction the material will be drawn to greater depths than along the 45° line, bringing the value of Δr for 0° and 90° above zero.

Where the anisotropy at 45° exceeds the other directionally oriented values, the inequality in the surface will be the most pronounced along that line, and the value of Δr will be driven under zero.

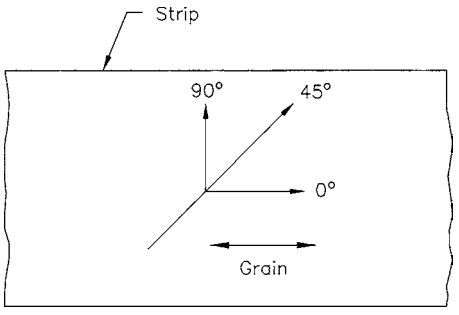

FIGURE 9-11 Anisotropy in a plane (surficial).

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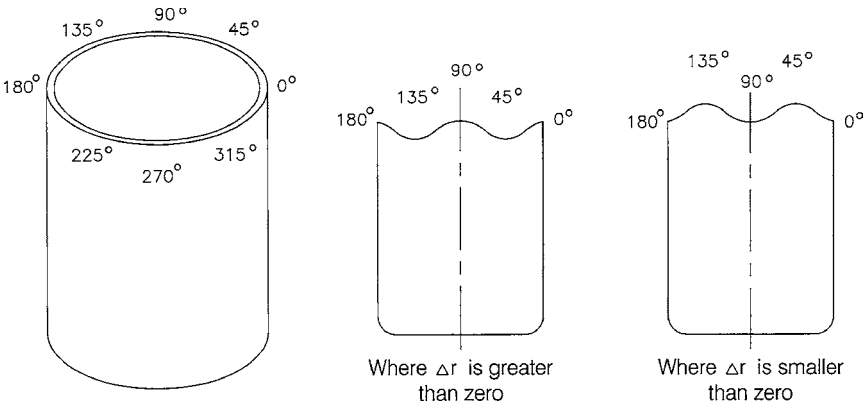

FIGURE 9-12 Uneven edges of drawn shells due to surficial anisotropy Δr.

9-3-2 Severity of Draw and Number of Drawing Passes

The severity of the drawing operation may be expressed by the relationship of the blank diameter to the cup diameter. This ratio, often called a *cupping ratio,* allows for an assessment of the amount of drawing passes needed to produce a particular shell.

Where this ratio is exceeded, a fracture of the shell results, attributable to the exhaustion of drawing properties of the particular material. This means that from a blank of a certain size, only a certain cup diameter and its depth may be produced during a single drawing pass.

The severity of draw is calculated using Eq. (9-4):

$$K = \frac{D_0}{d} \qquad \text{or} \qquad M = \frac{d}{D_0} \tag{9-4}$$

where K is the severity of draw factor and M is the reverse value of severity of draw factor.

Recommended values of M to be used for the first drawing pass are $M = 0.48$ to 0.60, with dependence on the drawn material properties.

The CSN 22 7301 (Czech National Standard, similar to DIN) recommends a range from

$$M_{\min} = \frac{50 + 0.01D_0}{100} \tag{9-5a}$$

up to

$$M_{\max} = \frac{60 + 0.01D_0}{100} \tag{9-5b}$$

The advantage of using the severity of draw calculations at the early stages of the drawn shell evaluation is the immediate assessment of the number of drawing passes needed.

Subsequent drawing passes may use the CSN 22 7301 recommendations of the M-value range, starting at

$$M_{n-\min} = \frac{70 + 0.01d_{n-1}}{100} \tag{9-6a}$$

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and up to

$$M_{n-\max} = \frac{80 + 0.01 d_{n-1}}{100} \tag{9-6b}$$

The total of all M coefficients for the particular drawing sequence is dictated by the geometry of all drawn and redrawn shapes and by the subsequent geometry of the finished shell. It may be calculated by using Eq. (9-7*a*):

$$M_{\text{total}} = M_1 \times M_2 \times M_3 \times \cdots \times M_n \tag{9-7a}$$

and subsequently

$$M_{\text{total}} = \frac{d_1}{D_0} \times \frac{d_2}{d_1} \times \frac{d_3}{d_2} \times \cdots \times \frac{d_n}{d_{n-1}} = \frac{d_n}{D} \tag{9-7b}$$

With a greater radius of the drawing die ranging between 8t and 15t, smaller values of the severity of the draw coefficient may be used. Subsequently, with smaller drawing die radii such as those ranging between 4t and 8t, larger coefficients are recommended.

For metals low in ductility, such as brass and some harder grades of aluminum, the coefficient should be made purposely larger and lowered for more ductile materials.

The height h of each step of drawing sequence (see Fig. 9-13) for various types of materials must be figured out, and perhaps even tested considering the material's properties.

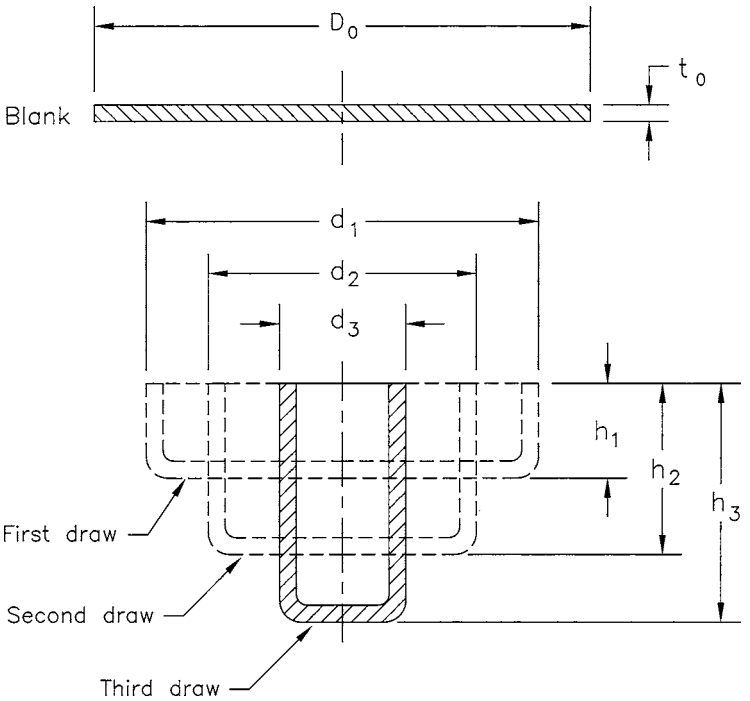

FIGURE 9-13 Drawing sequence. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

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Other guidelines are provided by the final part's dimensioning demands and restrictions. As already mentioned, sometimes annealing between the steps becomes necessary.

9-3-3 Cupping Strain Factor E_c

The strain factor of the cupping operation shows the actual strain in the metal created by its elongation during the deep-drawing process. For evaluation of this type of stress, Eq. (9-8*a*) should be utilized, perhaps in replacement of the severity of draw calculations included in the preceding section.

$$E_c = \frac{h}{H} = \frac{2(D^2 - d^2)}{4d(D-d)} = \frac{\dfrac{D}{d}+1}{2} \tag{9-8a}$$

Subsequently, to calculate the mean diameter of the cup d with respect to the allowable amount of the cupping strain factor, this formula can be written as

$$d = \frac{D}{2E_c - 1} \tag{9-8b}$$

The cupping strain factor, depicting the strain effect of cupping after the n-redrawing operation, is

$$E_{c,n} = \frac{h_n}{H_n} = \frac{t(D+d_n)}{2d_n t_n} \tag{9-9}$$

and the ultimate strain factor will be

$$E_{\max} = 1 + \frac{e}{100} \tag{9-10}$$

where e is the maximum elongation at fracture, percent.

Several recommended cupping ratios and their respective strain factors are shown in Table 9-1.

TABLE 9-1 Recommended Maximum Reductions for Cupping

Metal	Reduction in diam., % (max)*	Cupping ratio, D/d	Strain factor, $E_{c,n}$	Reduction in area, % (max)†
Aluminum alloys	45	1.80	1.40	28
Aluminum, heat-treatable	40	1.60	1.30	23
Copper, tombac	45	1.80	1.40	28
Brasses, high, 70/30, 63/37	50	2.00	1.50	33
Bronze, tin	50	2.00	1.50	33
Steel, low-carbon	45	1.80	1.40	28
Steel, austenitic stainless	50	2.00	1.50	33
Zinc	40	1.60	1.30	23

* $= 100(1 - d/D)$.
† $= 100(1 - a/A)$

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As each redrawing stage becomes progressively more impaired by the strain-hardening influence, the strain factor for each successive redrawing operation should always be smaller than the preceding one. Usually the first redrawing strain factor may be derived from the original E_c value by calculating

$$E_{\text{redraw}} = (E_c)^x$$

with the exponent x to be between 0.4 and 0.6. Usually a strain factor of 1.12 to 1.18 may be utilized in redrawing most materials.

In multioperational redrawing sequences, the total strain factor should be considered to be a multiple of the respective stress factors of all drawing operations.

This relationship may be expressed as

$$E_{c-\text{total}} = E_1 \times E_2 \times E_3 \times \cdots \times E_n \tag{9-11}$$

This means that should a total stress factor be $E_c = 1.4$, stress factors of various redrawing operations within the operational sequence should be chosen to equal their total multiple to 1.4.

The amount of stress factor value is mainly influenced by the ductility and strain hardening of the particular material. Where the total stress factor amount is reached sooner than the finished product is produced, annealing of the shell must be performed.

Singular strain factors—as may be seen from the formulas above—depend on ratios of the blank diameter to the shell diameter, or on the height of the drawn cup. The thickness of metal and the amount of friction within the particular drawing pass are also of importance in this process.

9-3-4 Reduction Ratios

A shell may be drawn into a certain depth only without a damage being caused to its shape or structure. Where greater depths or reductions are required, subsequent drawing passes must be added. To determine the amount of reduction per given shell size, the following formulas should be used.

For the first operation die:

$$d_1 = \frac{B_1 \times D}{100 - 0.635D} \tag{9-12a}$$

For all redrawing dies:

$$d_2 = \frac{B_2 \times d_1}{100 - 0.635d_1} \tag{9-12b}$$

$$d_3 = \frac{B_2 \times d_2}{100 - 0.635d_2} \tag{9-12c}$$

where D = blank diameter
d_1 = mean diameter of first shell
d_2 = mean diameter of second shell
d_3 = mean diameter of third shell
B_1 and B_2 = factors depending upon thickness of metal to be drawn, from Table 9-2

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TABLE 9-2 Factors B_1 and B_2

Stock thickness		First-operation die, B_1 value	Any redrawing die, B_2 value
in.	mm		
0.015–0.018	0.38–0.46	61	74
0.021	0.53	58	73
0.022–0.024	0.56–0.61	56	72
0.027	0.69	54	71
0.031	0.79	50	70–71
0.062–0.109	1.57–2.77	47	70
0.125–0.250	3.18–6.35	51	65

The reduction ratio R_c may be calculated by using the following formula:

$$R_c = \frac{100(D-d)}{D} \tag{9-13}$$

A graphical demonstration of the strain factor and blank dimension relationship for single- and double-action dies can be observed in Fig. 9-14. For visual representation of drawing sequence and terminology applicable to the above formulas, refer to Fig. 9-15. A rough assessment of the blank reduction in drawing can be ascertained by using the graph provided in Fig. 9-16.

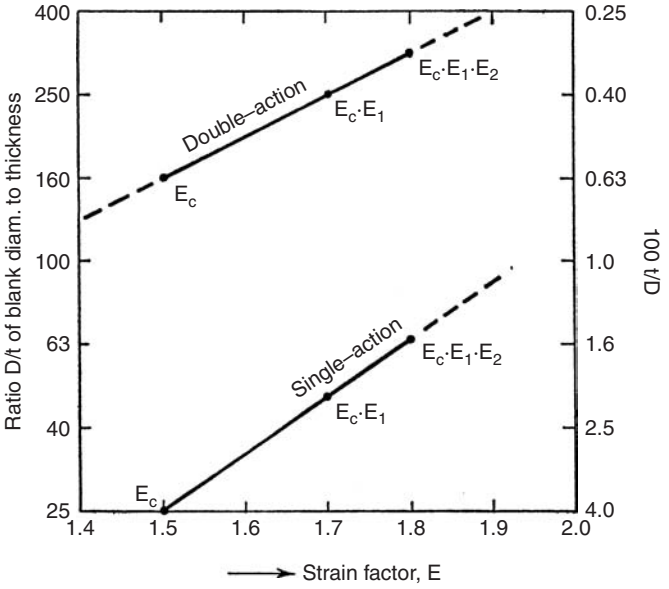

FIGURE 9-14 Relationship between strain factors and blank dimensions for deep drawing with single- and double-action dies. (*From: Frank W. Wilson*, Die Design Handbook, *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

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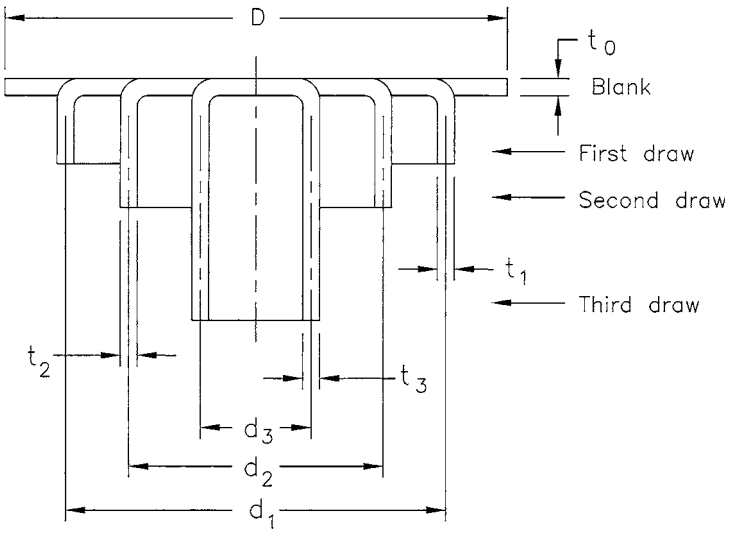

FIGURE 9-15 Drawing sequence.

9-3-4-1 Maximum percentage of reduction. A maximum percentage of reduction for deep-drawing materials of various thicknesses is slightly higher than the values included previously. Intermediate annealing is to be utilized only when the shells become strain hardened or when cracks begin to form.

Table 9-3, giving the values of the maximum possible reduction, should be used for dies operating in hydraulic presses, where the pressure of the blankholder is constant. The percentages given here are recommended for drawing operations only where no ironing is involved. Should ironing of the shell be needed, the values shown in Table 9-3 must be reduced.

TABLE 9-3 Maximum Percentage of Reduction for Deep-Drawing Materials

Stock thickness		First-drawing operation	Second-drawing operation	Any additional drawing operation
in.	mm			
0.010	0.25	27	18	17
0.015	0.38	32	20	19
0.021	0.53	35	21	20
0.024	0.61	39	22	21
0.031	0.79	42	23	22
0.036	0.91	44	26	24
0.042	1.07	46	28	25
0.046	1.17	47	28	25
0.054	1.37	47	29	26
0.062–0.124	1.57–3.15	48	30	27
0.125–0.250	3.18–6.35	47	28	26

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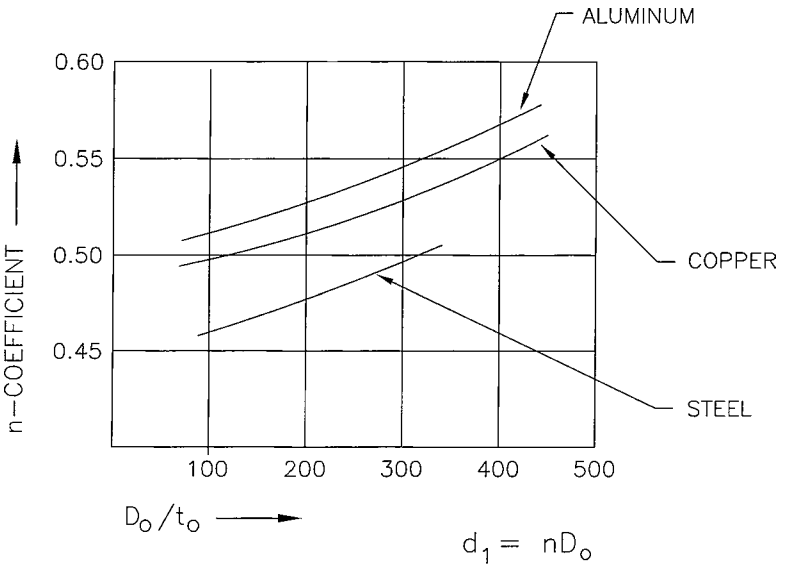

FIGURE 9-16 Graphical method of blank reduction in drawing.

9-3-4-2 Drawing of Stainless-Steel Shells. Drawing of stainless-steel shells may basically follow the same procedures as drawing of other materials. But a slight change in reduction formulas is necessary, for in the drawing process, stainless steel behaves differently from other materials.

For example, a large reduction from the basic flat blank is possible for stainless steel of 18-8 type, but the subsequent drawing operations must be very moderate.

A chromium type 17-20 steel cannot be drawn into great depths from a blank, yet larger reductions may be obtained through succeeding redrawing operations.

Generally, chromium-nickel stainless steel strain hardens quite readily, for which reason more frequent anneals, combined with lower drawing speeds and better lubrication, are required.

The amount of reduction of the particular stainless-steel material may be calculated with the help of constants $B_{SS\text{-}1}$ and $B_{SS\text{-}2}$, listed in Table 9-4.

TABLE 9-4 Factors $B_{ss\text{-}1}$ and $B_{ss\text{-}2}$

Material thickness		First-operation die, $B_{ss\text{-}1}$ value		Any redrawing die, $B_{ss\text{-}2}$ value	
in.	mm	18-8 SS	17Cr SS	18-8 SS	17Cr SS
0.015–0.018	0.38–0.46	61	68	81	77.5
0.021	0.53	58	65	80	76.5
0.022–0.024	0.56–0.61	56	63	80	75.5
0.027	0.69	54	60	79	74.5
0.031	0.79	50	56	77	74
0.062–0.109	1.57–2.77	47	53	75	73.5
0.125–0.250	3.18–6.35	51	51	65	65

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Annealing between drawing stages is required for stainless. The preferred press equipment to be used is a double-action press or a single-action die with a drawing collar and an air cushion.

The formula for obtaining the maximum reduction in stainless-steel material to be used for the first operation die is

$$d_1 = \frac{B_{ss\text{-}1} D}{100 - 0.625D} \tag{9-14a}$$

And for all succeeding redrawing dies:

$$d_2 = \frac{B_{ss\text{-}2} d_1}{100 - 0.625 d_1} \tag{9-14b}$$

and

$$d_3 = \frac{B_{ss\text{-}2} d_2}{100 - 0.625 d_2} \qquad \text{and so on.} \tag{9-14c}$$

where D = blank diameter
d_1 = mean diameter of first shell
d_2 = mean diameter of second shell
d_3 = mean diameter of third shell, and so on
$B_{SS\text{-}1}$ and $B_{SS\text{-}2}$ = constants, depending upon the thickness of metal to be drawn, from Table 9-4

Stainless steel is an interesting material to work with, as it has its own mysteries and surprises. Already the fact that some nonmagnetic stainless steel turns positively magnetic after second or third drawing sequence, is worth pondering upon.

9-3-5 Strain Hardening of Material

The research has asserted that the strain-hardening coefficient has a dual effect on the formation of wrinkles in drawn material. First, it enhances the material's resistance to wrinkling through its supportive action toward the buckling modulus. Further, it affects the distribution of strain, caused by the action of drawing, while supporting the development of higher compressive stresses within the walls of shells.

To eliminate the effect of strain hardening, radial tension in the walls of the drawn part must be enhanced, and the die radius should be decreased. Also the blankholder's pressure has to be increased, while lower-grade lubricants should be utilized.

Wrinkling of drawn parts usually begins quite close to the die radius; that's where the compressive stresses within the material are the largest. Where the pressure of the blankholder is inadequate, these wrinkles will increase; but with higher blank-holding pressure, fracturing of metal covering the tip of a punch will occur.

In cold-rolled steels and high-strength low-alloyed materials the limitation in drawing depth due to fractures or wrinkling was already established. In high-strength low-alloyed materials, the tendency to wrinkling is known as well, which—in order to be prevented—will demand higher blank-holding pressures applied against the blank.

In martensitic stainless steel, the strain-hardening tendency of the material decreases as the temperature rises. Yield stress can be lowered by the use of coarse-grained material, provided its surface layer is not as coarse as so-called "orange-peel" texture. Coarsely grained material also displays an increase in its ductility.

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Uniformity of the strain distribution within the material, as well as a decrease of its strain-hardening tendencies, will be affected by choosing a material with quite a high carbon content, 0.1 percent and up. An equal distribution of the peak uniform strain depends also on the carbon content, most probably because of carbon's strengthening effect in strain-induced martensite materials.

With forming of deep stainless-steel shapes, using a 302 type of material, 50 to 60°C was measured in critical areas of the product. At such a temperature range, a strain of highest uniformity may be obtained in steels with 1.0 austenite stability factor.

Generally, slight variations in the strain rate values do not affect the strain-hardening tendency of the material. That tendency, along with the level of peak uniform strain and yield stress, can be increased by elevating the material's carbon and nitrogen content.

9-3-5-1 Strain Hardening–Related Calculations. The strain factor of the material E, when equal to 1.0, is applicable to the annealed metal of the yield strength S_o. With strain-hardened metal, the E_{max} value, which is the ultimate strain factor [see Eq. (9-10)] will enter the picture, accompanied by the ultimate tensile strength S_u. For purposes of calculation, these material data can be obtained from the mill where the steel was produced.

A comparison of strain hardening, strain factor, tensile strength, and diametral reduction can be found in Fig. 9-17. The drawn shell's tensile strength S_c may be obtained as

$$S_c = S_o \log_e E_c^n \tag{9-15}$$

where n is the strain-hardening exponent.

The strain-hardening exponent n determines the plastic limit or ultimate strength of the material usually avoided in general deep drawing practice. Ultimate strength, with elastic limit, hardness, and yield point, increase when the strain factor of cupping E_c increases.

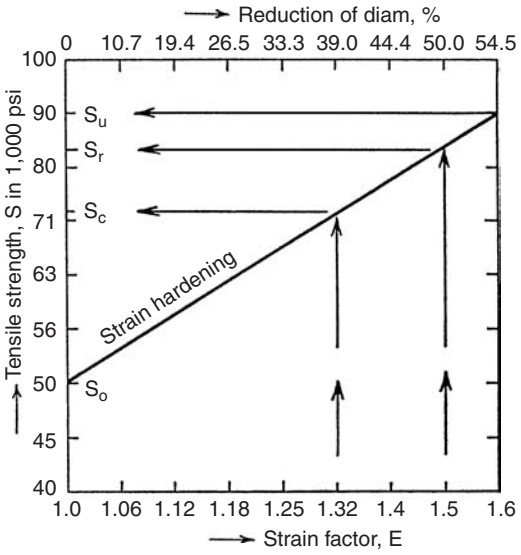

FIGURE 9-17 Relationship between strain hardening, strain factor, and tensile strength. (*From: Frank W. Wilson*, Die Design Handbook, *New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

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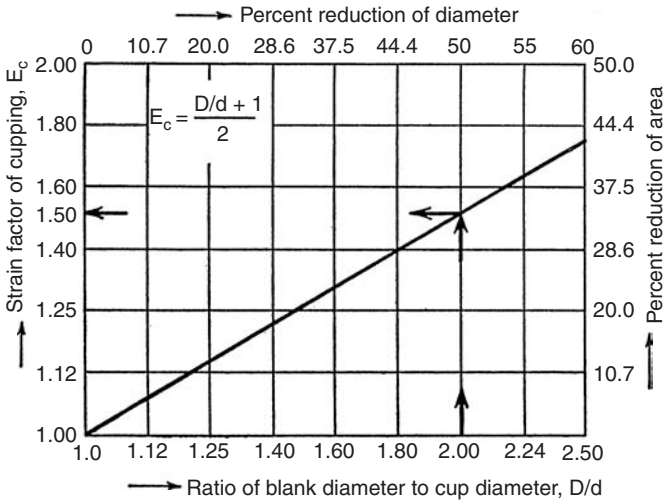

FIGURE 9-18 Relationship between cupping ratio D/d and the strain factor of cupping E_c (logarithmic base). (*From: Frank W. Wilson*, Die Design Handbook, *New York, 1965. Reprinted with permission from The McGraw Hill Companies*.)

With the cupping strain factor $E_c = 1.32$, a tensile strength of $S_c = 71{,}000$ lb/in.^{2} is encountered in the upper portion of the shell, which is known to be the most strained area. Choosing a safe value for the total strain factor as $E_{c\text{–total}} = 1.5$ results in tensile strength in the cup's upper part of $S_c = 82{,}000$ lb/in.^{2}. From these assumptions, an appropriate redrawing strain factor may be computed by using Eq. (9-11) as

$$E_1 = \frac{E_{c\text{–total}}}{E_c} = \frac{1.5}{1.32} = 1.14$$

The logarithmic relationship of the cupping ratio D/d comes out as a straight diagonal line, shown in Fig. 9-18.

9-3-6 Wall Thickness Decrease or Ironing

Some products can be designed with an intentional decrease in their wall thickness, to be attained during deep drawing. This decrease may often be considerable, in which case several drawing passes are needed if these shells are to be produced using either conventional processes or alternative manufacturing methods such as extruding or reverse drawing.

Shells of smaller diameters may be deep-drawn with an addition of thinning, or ironing of their walls. The number of necessary drawing passes depends on the ratio of the wall thicknesses before and after drawing, and it is influenced by the maximum possible deformation of the material. Equation (9-16) should be used to calculate deformation

$$F = 100\frac{t_{n-1} - t_n}{t_{n-1}}(1 - k_t)\% \qquad (9\text{-}16)$$

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TABLE 9-5 Ironing-Related Deformation (F) (Percentages)

Material	First draw		Second draw	
	F	k_t	F	k_t
Steel, annealed	55–60	40–45	35–40	50–55
Steel, medium hard	35–40	55–60	25–30	65–70
Aluminum	55–60	35–40	40–50	50–55
Brass	60–65	30–40	50–60	40–50

where F = allowed deformation per Table 9-5.
t_n and t_{n-1} = wall thickness per Fig. 9-19. The n denotes the sequential number of the draw, 1, 2, 3, . . ., n
k_t = thinning coefficient, obtained from Eq. (9-17).

$$k_t = 100\frac{t_n}{t_{n-1}}\% \tag{9-17}$$

Changes in the wall thickness and shell diameter can sometimes be quite radical, as shown in Fig. 9-20.

Today's manufacturing methods allow for a combined drawing in a single die, using various inserts in succession, to achieve the desired decrease in the product wall (Fig. 9-21). Since the friction between material and tooling may be considerable in such a case, parts are coated prior to drawing with copper or phosphate coatings.

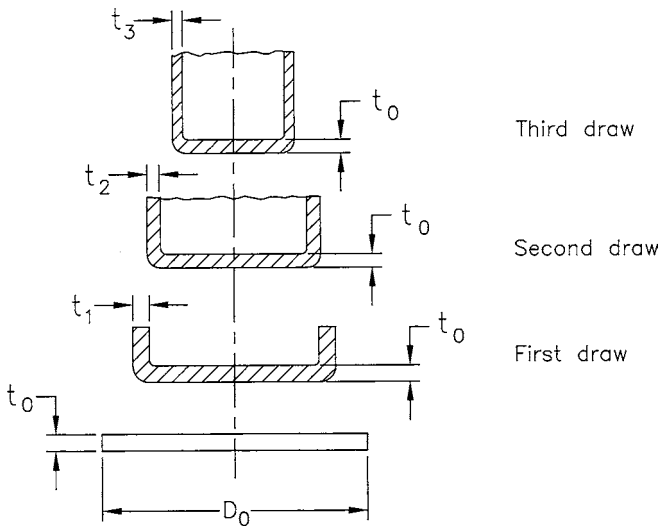

FIGURE 9-19 Drawing sequence with thinning of the wall. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

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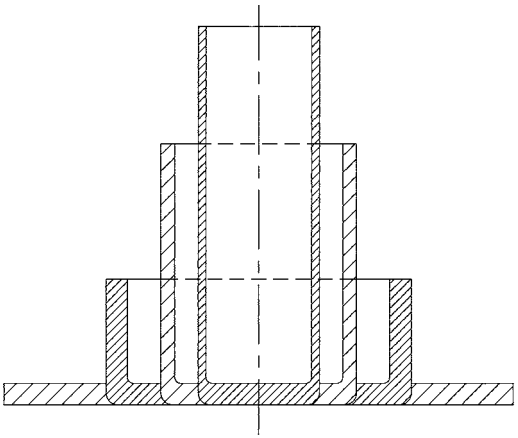

FIGURE 9-20 Drawing operations with thinning of the wall.

9-3-7 Forming of Flanges

Various blanks may be drawn into impressive depths, provided a correct material type is chosen, the tooling design is sound, and the manufacturing procedures and the choice of press are acceptable. All drawn products can be placed in two groups:

- Drawn shells with flanges
- Drawn shells without flanges

Where flanges are to be produced on a drawn shell, the size of the blank must be adequate to suffice for their width, often leaving some additional material for trimming. Trimming of the drawn cup with a flange is usually inevitable, for the outer edge of the blank may become distorted by the drawing process (Fig. 9-22).

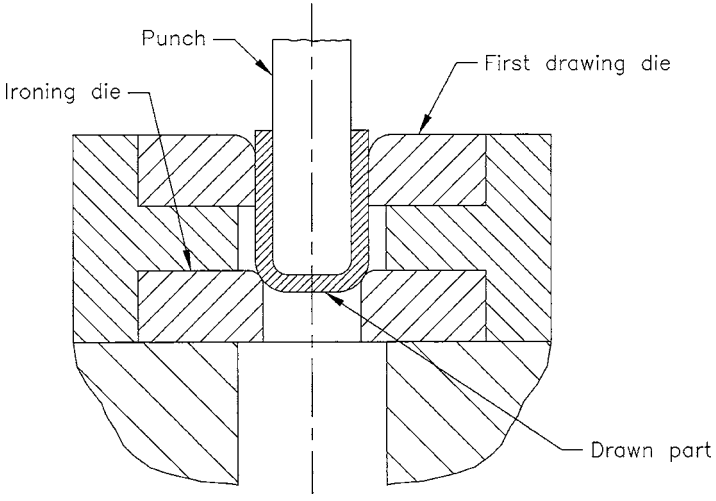

FIGURE 9-21 Two drawing inserts in a single die.

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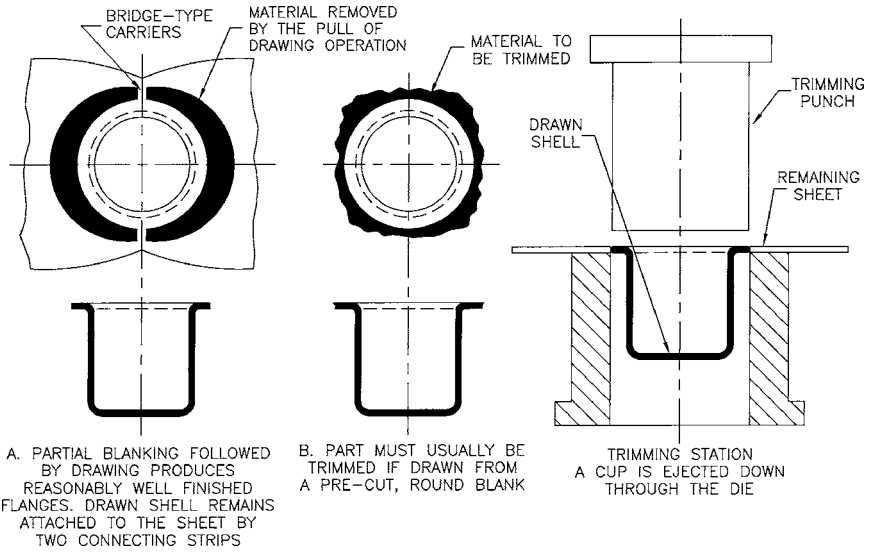
BRIDGE–TYPE CARRIERS
MATERIAL REMOVED BY THE PULL OF DRAWING OPERATION
MATERIAL TO BE TRIMMED
TRIMMING PUNCH
DRAWN SHELL
REMAINING SHEET
A. PARTIAL BLANKING FOLLOWED BY DRAWING PRODUCES REASONABLY WELL FINISHED FLANGES. DRAWN SHELL REMAINS ATTACHED TO THE SHEET BY TWO CONNECTING STRIPS
B. PART MUST USUALLY BE TRIMMED IF DRAWN FROM A PRE–CUT, ROUND BLANK
TRIMMING STATION A CUP IS EJECTED DOWN THROUGH THE DIE

FIGURE 9-22 Flange trimming.

Trimming of the flange is performed in the last operation of the sequence, where the finished part is also ejected out of the die. Sometimes a pinch-trim of the shell is preferred, because of its speed and simplicity of operation (Fig. 9-23).

Where parts without flanges are to be drawn, the blank size for their production should be exact, with no material to be removed afterward. This way the material volume gets all used up in the drawing process. The finished shell may be ejected from the die in a last drawing stage, where it is dropped down on return of the punch (Fig. 9-24).

This type of ejecting method uses various types of strippers, that prevents the formed cup from following the movement of the punch. Some samples of such stripping arrangements are discussed in Sec. 4-2-5.

The method of drawing shells with flanges can be divided into three basic procedures of their production:

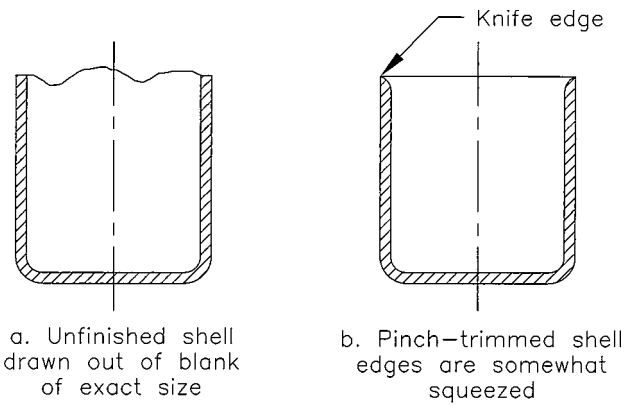

FIGURE 9-23 Finishing of shells without flanges.

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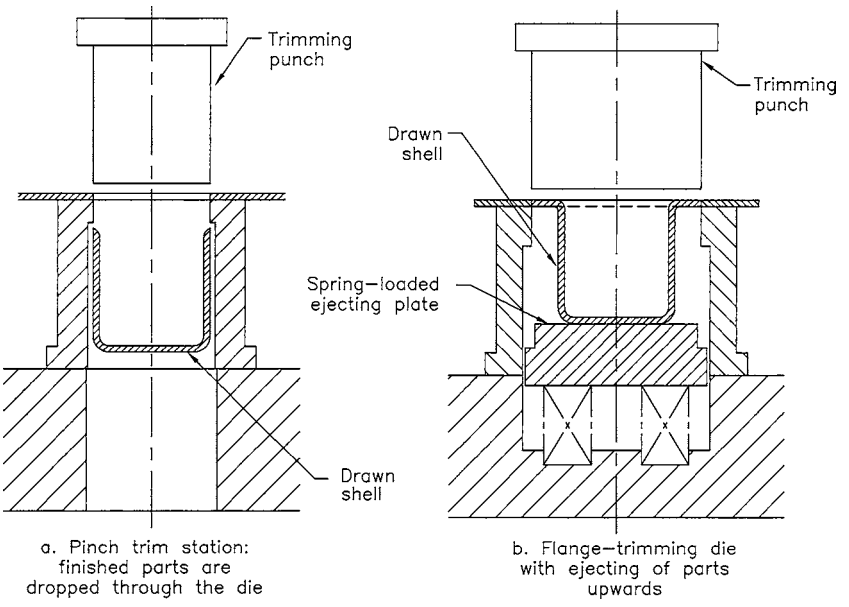
Trimming punch
Drawn shell
Spring–loaded ejecting plate
Drawn shell
a. Pinch trim station: finished parts are dropped through the die
Trimming punch
b. Flange–trimming die with ejecting of parts upwards

FIGURE 9-24 Ejecting of drawn shells.

1. First, where the diametral reduction of the flange is not of concern, the blank may be drawn into the desired shape and depth by drawing and redrawing until a finished part is produced. Each drawing stage slightly reduces the blank diameter, utilizing the material for the depth of the shell. The width of a flange is not affected, but its overall diameter diminishes.

Such a procedure subjects the material to a greater strain, created by excessive stretching of both the flange and the cup. The strain-hardening effect is increased, with more annealing required between redraws. Nevertheless, this is the most commonly used drawing practice (Fig. 9-25).

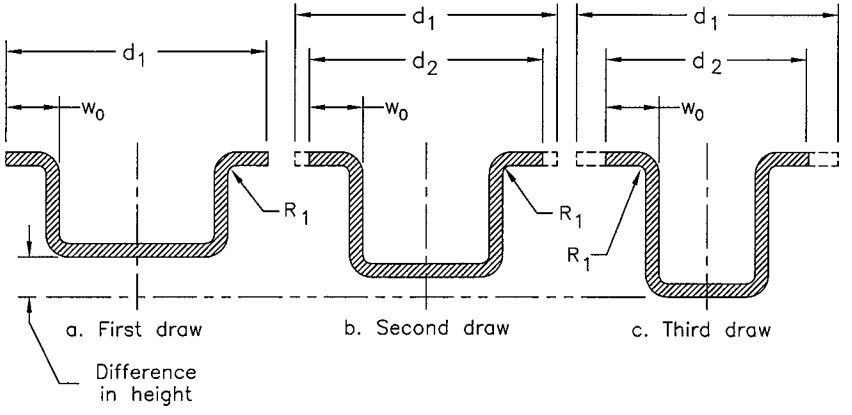

FIGURE 9-25 First method of shell drawing.

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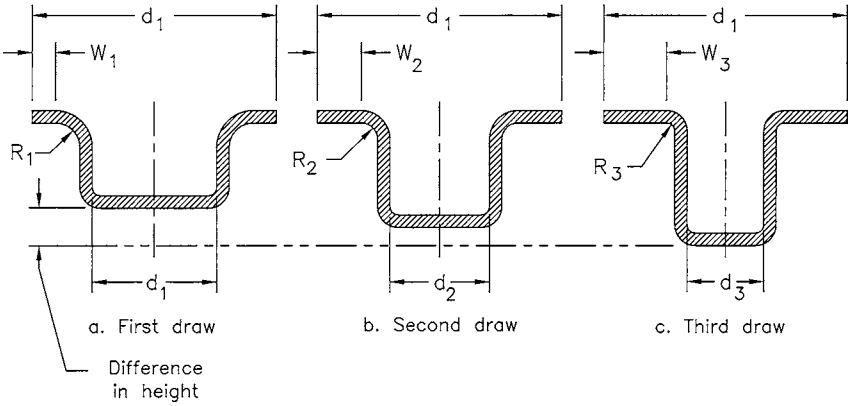

FIGURE 9-26 Second method of shell drawing.

2. The second drawing method keeps the blank diameter intact while increasing the width of the flange with each redrawing pass (Fig. 9-26). This method should be used where the diameter of the flange is considerably larger than the diameter of the shell.

During the drawing process, a portion of the material is actually forced back into the flange with each decrease of the shell diameter. This is achieved by making a radius of the first drawing die as large as possible, with all subsequent radii reduced in size. Such an alteration promotes the upward flow of metal, keeping the wall thickness more uniform and creating less strain within the material structure, which subsequently decreases the number of annealings needed.

Care should be taken when adjusting the stroke of a press so that it does not exceed the required depth, for if the punch begins to draw the material in each redrawing operation, it certainly will pull the material from the flange.

3. The third method involves the shells with wide flanges, which often pose a problem in the drawing process, as the tendency to form wrinkles is sometimes difficult to overcome. Therefore, an adjustment in the drawing procedure should be made to allow for the allocation of metal to be drawn partially from the flange as well as from the body of the shell (Fig. 9-27).

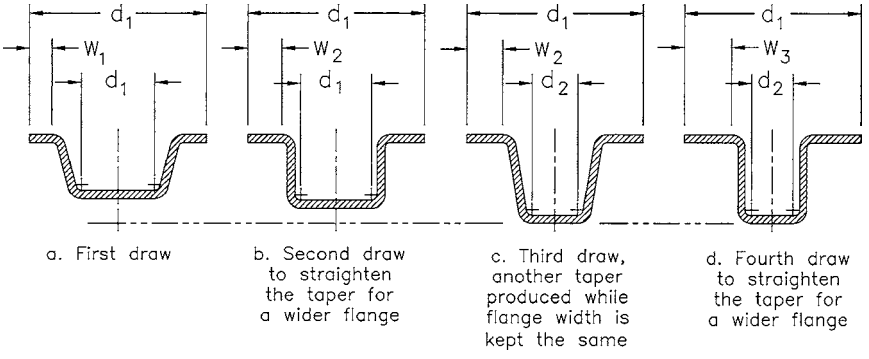

FIGURE 9-27 Third method of shell drawing for wide-flanged parts.

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Here the depth is produced in the first drawing operation, leaving the shell with tapered walls. The second draw straightens the sides of the cup, pushing the excess material into the flange, which turns wider. In the third drawing station the bottom diameter is drawn smaller in size, the excess material being allocated for a production of another inclination of the wall. The last drawing pass straightens the wall, pushing the excess material toward the flange.

9-3-8 Height of a Shell

The height of the shell consists of a displaced metal taken mainly from the flange and more or less from the other areas of the blank. Where no thinning of walls is encountered, the bottom of the shell remains unaltered, with no metal being removed or added there.

The maximum height attainable from a given blank size can therefore be calculated. For the purpose of simplicity this evaluation is approximate, where the corner radii are neglected and the shell thickness is considered equal to that of the blank in all its cross-sectional areas. In such a case, the height will be

$$h = \frac{D^2 - d^2}{4d} \tag{9-18a}$$

where h = height of shell
D = blank diameter
d = mean diameter of shell

The height of a shell subjected to n-redrawing operations may be calculated:

$$h_n = \frac{t\left(D^2 - d_n^2\right)}{4d_n t_n} \tag{9-18b}$$

Obviously, d_n is the mean diameter of the shell after n-redraw and t_n is the thickness of the wall then, while t is the original thickness of the blank.

9-3-9 Drawing Speed

While other die processes are not overly affected by the actual speed, the drawing operation is speed-dependent with respect to the material drawn. Where zinc is included in the material buildup, a slower drawing rate should be chosen. Such speed is also beneficial for drawing of austenitic stainless steel. With aluminum- and copper-based materials, greater speeds are possible.

Generally used drawing speeds for single-action and double-action dies fall within a range of values as shown in Table 9-6.

Exceeding the limits of drawing speed can impair the quality of produced parts, as inadequate flow of material will be obtained. An approximate drawing speed (Speed_{DR}) can be calculated as follows:

$$\text{Speed}_{\text{DR}} = 2L_{\text{ST}}(\text{PS/min}) \tag{9-19}$$

where L_{ST} is the length of the press stroke and PS/min is the number of strokes per minute.

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TABLE 9-6 Drawing Speeds

Material	Single-action drawing, in./sec	Double-action drawing, in./sec	Single-action drawing, m/sec	Double-action drawing, m/sec
Steel	12	6–10	0.3	0.15–0.25
Stainless steel	8	4–6	0.2	0.1–0.15
Aluminum alloys	10	6–8	0.25	0.15–0.2
Copper	30	17	0.75	0.45
Brass	35	20	0.9	0.50

9-3-10 Forming Limits

Forming limits of sheet-metal material are not easy to assess. First of all, there is the influence of forming tooling quality, its clearance, and surface finish. Additionally, there are other variables at play, such as the springback of the material, residual stresses and resulting structural changes, mechanical properties of the material, and others. Together, these can create enough "unknowns," all of them exerting their portion of influence on a formed part in a highly unpredictable way.

The *finite element analysis* (FEA) is nowadays being used where possible to indicate such areas of concern. Already in the development stage, parts are often designed in a 3D software, where their functionality under various stresses can be evaluated. Their reaction to loading at critical points, taking into account the shape of the part and all its cutouts, or the cyclic loading and resistance to thermal or electrical differences can be evaluated by an unrelenting, ever precise computer software. But even such a fully trustworthy tool can fail when not taking into account the least of the influences described in the previous paragraph. Already a change of lubricant can produce quite different results than those the FEA and other analyses may anticipate.

Perhaps for these reasons a down-to-earth method of formed material limits' evaluation was developed by Stuart Keeler sometimes in the late 60s. This method takes into account the true shop surroundings and subjects the tested material to the actual process of drawing, utilizing the same tooling that will be used in production.

A circle-grid analysis is used as an evaluating tool. It starts with a grid of circles, etched onto the surface of a sheet-metal material, as shown in Fig. 9-28. After drawing, some circles

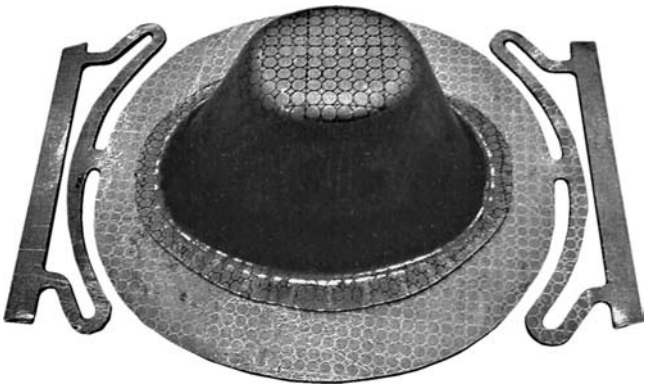

FIGURE 9-28 Etched blank. This blank has been etched using circle grid analysis (*From: The STAMPING Journal®, May/June 2001, page 60, by Art Hedrick. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

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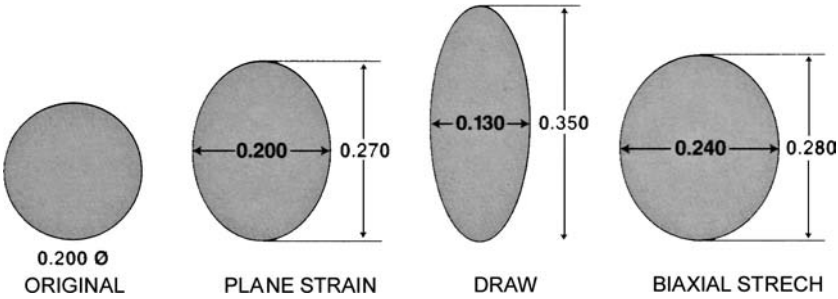

FIGURE 9-29 Circles used in the circle grid analysis, showing the original shape, plane strain, draw, and biaxial stretch. These are some of the basic metal deformation modes most common to sheet metal. (*From: The STAMPING Journal®, May/June 2001, page 60, by Art Hedrick. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

can be found stretched in various directions, per Fig. 9-29. These values are plotted into a forming limits diagram (Fig. 9-30), which shows the amount of deformation a part was subjected to. Tightening the conditions of drawing operation, circle-grid analysis can be used to evaluate the maximum amount of deformation a part can be subjected to before the material fails.

Where the etched circles deform to show any distortion, such deformation is always strain-induced. The deformation under a strain can be *planar*, which refers to a deformation along a single axis only; or it can be *biaxial*, where the changes can be seen along both axes of the circle. The biaxial deformation, or biaxial stretch can also be called a *drawing deformation*.

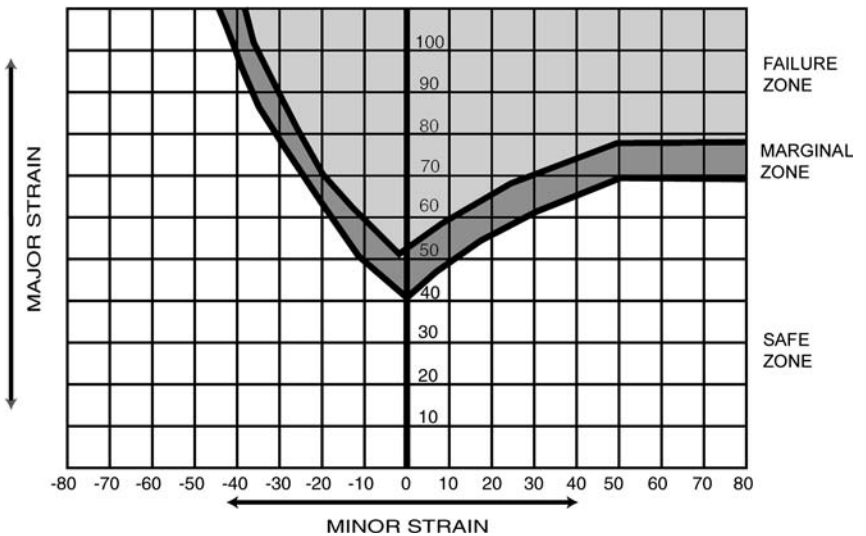

FIGURE 9-30 Forming limit diagram. Plotted results of the etched circles measurements after forming or drawing. (*From: The STAMPING Journal, May/June 2001, page 60, by Art Hedrick. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

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The ever-present work hardening of metal depends on the severity of draw, which is commenced by the mechanical properties of that particular material. Such influences will demonstrate themselves on the circle grid pattern as nonuniform disruptions. These should be avoided by changing the tooling geometry and configuration, otherwise twisting, bowing, and such deformations of parts may result.

9-4 DRAWING OF CYLINDRICAL SHELLS

A generally accepted definition of deep drawing is that the drawn part's or cup's length is greater than half its diameter. At such a difference from the flat blank, one can anticipate the changes that must occur within the material structure to bring about this extension of shape.

Drawing of round shells seems simple enough, yet the amount of influencing factors renders this operation no less difficult than any other drawing process. Already the fact that a blank of a correct size will come out of the drawing process with wavy edges (in flangeless shells) and often has to be trimmed to certain height, brings about a host of dilemmas pertaining to the trimming method and its control. Where a flange has to remain on the drawn cup, other problems, such as those of flange retention, trimming, and ejecting of parts, may be encountered.

First of all, the blank size must be addressed with care and often several calculations must be performed and supported by testing, before the final drawing tool can be constructed.

9-4-1 Blank Size of a Drawn Shell

The displacement of metal in drawing operations varies along the shape of a shell. The flange is subject to the greatest alterations, while the bottom remains almost unchanged.

The metal flow during the drawing process promotes the increase in height of a part toward which it is applied. Whole segments shift away from the flange area into the body of the shell. The surface most affected by such changes is that located farthest away from the shell body, which is the outer surface of the flange.

To calculate the basic size of a blank from which—through such transformation—a drawn cup may be obtained, the area of the part has to be assessed, which then will be projected into a diametral size of the blank.

Two methods of blank calculation, both applicable only to symmetrical shells, are described further. The first method is based on a theory that the area of any shape is given by the length of its profile, multiplied by the length of travel of its center of gravity.

9-4-1-1 First Method of Blank Calculation. Lengths of line segments L_1, L_2, and L_3, as shown in Fig. 9-31, should be assessed along their neutral axis. Distances of their centers of gravity along X axis, X_1, X_2, X_3 should be established. The formula to calculate the linear distance of the center of gravity (CG) of the shape is

$$X = \frac{L_1X_1 + L_2X_2 + L_3X_3}{L_1 + L_2 + L_3} \tag{9-20}$$

As there is no need to calculate the distance of the center of gravity CG along the Y axis, it will not be attempted here.

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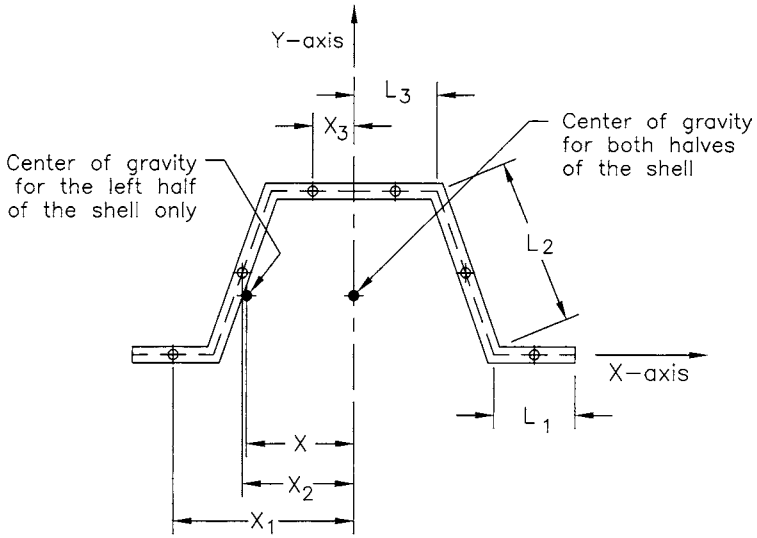

FIGURE 9-31 First method of blank calculation.

The total length of the shape can be obtained by adding all segment lengths together. Multiplying this value by the length of the circular path of the *CG* can be done by using the formula

$$A = 2\pi X(L_1 + L_2 + L_3) \tag{9-21}$$

From the result, a blank diameter may be acquired:

$$D = 2\sqrt{\frac{A}{\pi}} = \sqrt{8XL_{\text{total}}} \tag{9-22}$$

9-4-1-2 Second Method of Blank Calculation. The second method of blank computation calculates each section of the drawn shell separately, adding their lengths up (Fig. 9-32).

Both of these methods give only an approximate size of the blank diameter, since to calculate its exact proportions is nearly impossible. Too many variables influence the drawing process, making it more complex than any other manufacturing method. The movement of metal, which may produce thickening or thinning of various sections, a possibility of ironing, the variation in height, are a few factors out of many that expose the drawn part to so many influences that the total outcome is unpredictable.

Therefore, the blank size is usually chosen either slightly larger than necessary and trimmed afterward or an exact blank size may be considered, which is further adjusted in size after completion of a trial run.

The following set of calculations considers the size of blank diameter for simple cylindrical shells to be dependent on the ratio of the shell diameter to the corner radius d/R. It regards the blank to be of the same surface area as the finished shell.

where $d/R = 20$ or more, the calculation to use is

$$D = \sqrt{d^2 + 4dh} \tag{9-23a}$$

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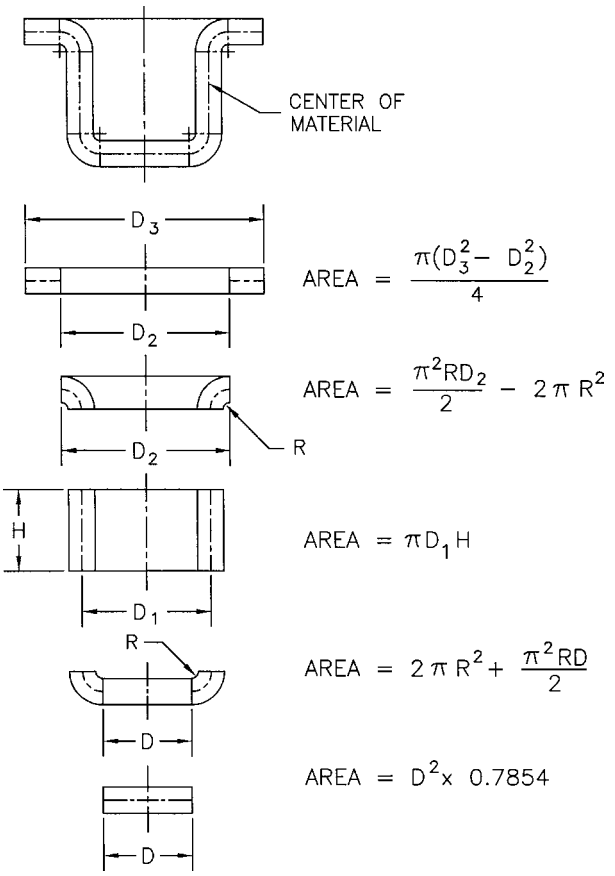

FIGURE 9-32 Second method of blank calculation.

with $d/R =$ 15 to 20, the following formula should be used:

$$D = \sqrt{d^2 + 4dh} - 0.5R \tag{9-23b}$$

where $d/R =$ 10 to 15, the formula is

$$D = \sqrt{d^2 + 4dh} - R \tag{9-23c}$$

And where $d/R =$ below 10, the calculation becomes

$$D = \sqrt{(d - 2R)^2 + 4d(h - R) + 2\pi R(d - 0.7R)} \tag{9-23d}$$

Some recommend a formula for calculating all types of drawn shell blanks as

$$D = \sqrt{d^2 + 4dh - 3.44dR} \tag{9-23e}$$

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where D = blank diameter
d = shell diameter
h = height of shell
R = radius of corner

For shells where some ironing is expected, resulting in thinner walls than the bottom surface, the following blank size calculation may be used:

$$D = \sqrt{d^2 + 4dh\frac{t_w}{t_B}} \tag{9-24}$$

where t_B is the thickness of bottom area or that of a blank and t_W is the thickness of wall.

For an evaluation of more complex shell shapes, their cross-sectional outline should be dismembered to obtain simple sections whose areas can be calculated with the aid of formulas in Figs. 9-33 and 9-34. The total blank size is obtained by adding up all results.

9-4-2 Clearance Between Punch and Die

If a gap between a punch and die is too generous, the material will not be in contact with both parts of tooling simultaneously. The drawing operation will be altered because of such a discrepancy, and the process will rather resemble stretching.

An insufficient clearance between the tooling will produce thinner walls, which is an effect called *ironing*. Ironing is sometimes used on purpose, where an improvement in the shell surface is needed. Too small a clearance prevents the material from relocating freely within the thickness of the part, which promotes its compacting and compressing.

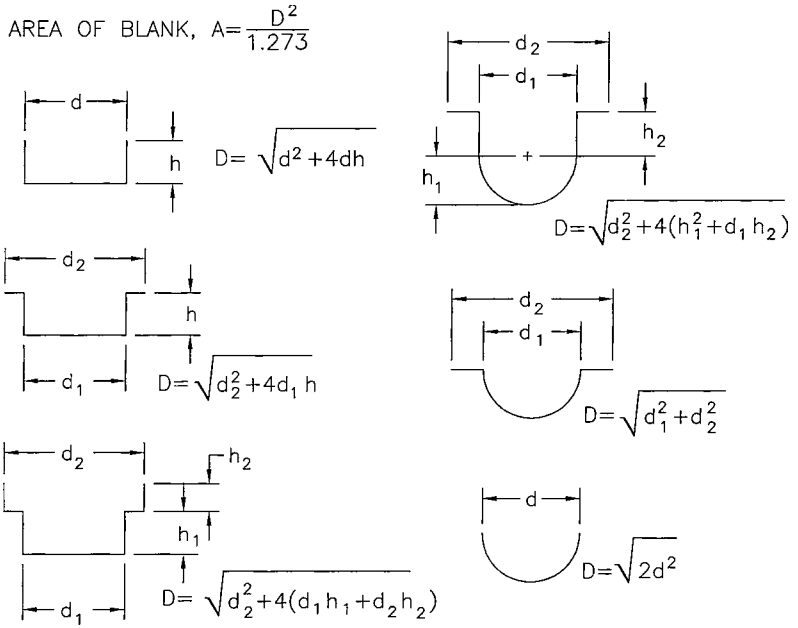

FIGURE 9-33*a* Blank diameter calculation.

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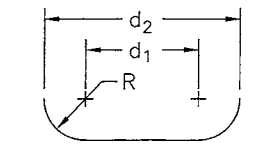
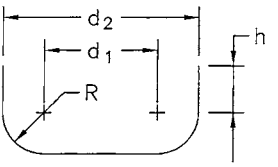
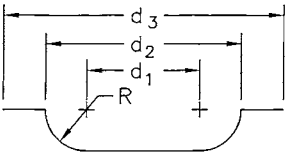
AREA OF BLANK, $A=\frac{D^2}{1.273}$



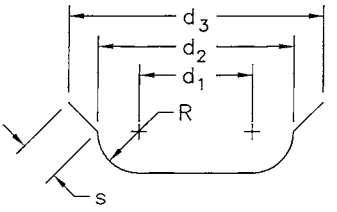
$$D=\sqrt{d_1^2+6.28Rd_1+8R^2}$$



$$D=\sqrt{d_1^2+6.28Rd_1+8R^2+4d_2h}$$



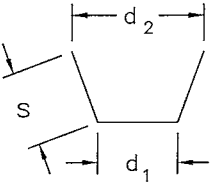
$$D=\sqrt{d_1^2+6.28Rd_1+8R^2+d_3^2-d_2^2}$$



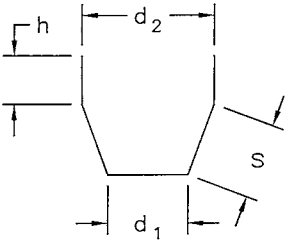
$$D=\sqrt{d_1^2+6.28Rd_1+8R^2+2s(d_2+d_3)}$$

FIGURE 9-33*b* (*Continued*)

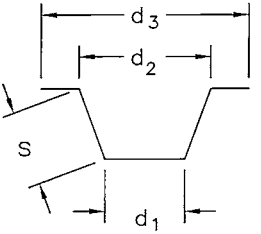
AREA OF BLANK, $A=\frac{D^2}{1.273}$



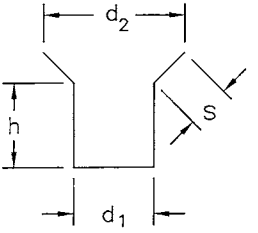
$$D=\sqrt{d_1^2+2s(d_1+d_2)}$$



$$D=\sqrt{d_1^2+2[s(d_1+d_2)+2d_2h]}$$



$$D=\sqrt{d_1^2+2s(d_1+d_2)+d_3^2-d_2^2}$$



$$D=\sqrt{d_1^2+4d_1h+2s(d_1+d_2)}$$

FIGURE 9-33*c* (*Continued*)

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DRAWN PARTS

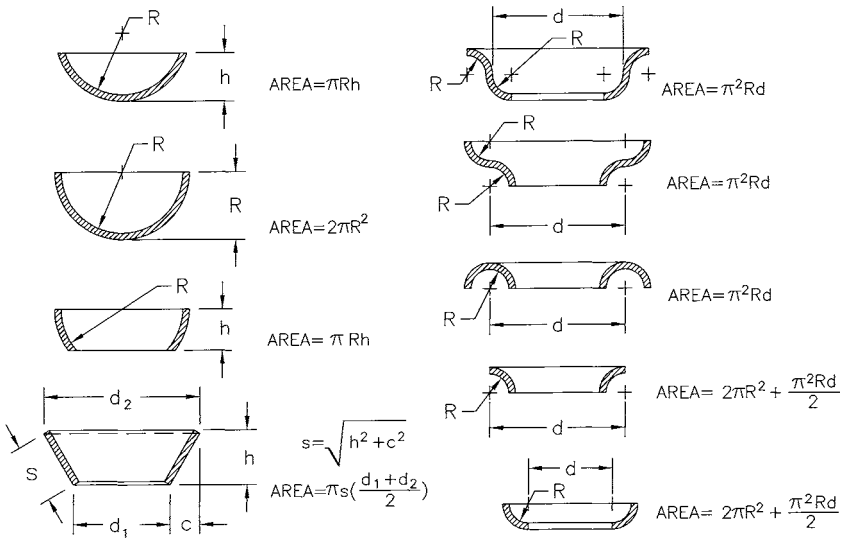

FIGURE 9-34 Areas of drawn shells through center of stock.

The generally recommended clearance between the drawing punch and die should be in the vicinity of

$$z = \text{clearance} = 1.4t$$

or 40 percent greater space than the material thickness. Clearance may be smaller for flanged shells than for those having no flange and being pushed out through the die.

The CSN 22 7301 (Czech National Standard, similar to DIN) suggests

$$z = 1.2t_{\max}$$

Oehler's recommendation is given by a formula

$$z = t_{\max} + k\sqrt{10t_0} \tag{9-25}$$

where $k = 0.07$ for steel,
$k = 0.04$ for nonferrous metals, and
$k = 0.02$ for aluminum
t_0 = original blank thickness

The clearance, however, depends mainly on the material to be drawn. In Table 9-7, some basic guidelines are given, differentiating the material influence in drawing.

Tolerances, allowing for a slight ironing action, such as those using the gap size between $1.1t$ and $1.2t$, are often used within the industry. In such a case, the wall of the drawn shell will come out slightly thinner, but its straightness and uniformity of thickness are usually beneficial to the outcome, even where a redrawing station has to be utilized.

Another evaluation of the ironing operation recommends the diameter of the ironing die to be

$$DIA_{\text{die}} = DIA_{\text{punch}} + 2t + 0.004 \text{ to } 0.008 \text{ in. } [0.10 \text{ to } 0.20 \text{ mm}]$$

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TABLE 9-7 Clearance between the First Drawing Punch and Die for Cylindrical Shells

Material	Per-side clearance between punch and die
Aluminum	1.25t
Steel, deep drawing	(1.1 to 1.25)t
Stainless steel	(1.75 to 2.25)t

*t = stock thickness.

Such a clearance should provide a smooth finish or accurate outer diameter of the shell. Where a finer finish is needed, the diameter of the ironing die should be

$$DIA_{\text{die}} = DIA_{\text{punch}} + 2t + 0.002 \text{ in. } [0.05 \text{ mm}]$$

Ironing of the shell with the intention of reducing the material thickness necessitates drawing of the shell to the required inside dimensions, and ironing in a separate die. The ironing process considerably increases the pressure of the punch against the bottom of the shell. For that reason, the diametral reduction of each redrawing station should be smaller than that used for redrawing with no ironing. One-half of the amount needed for drawing without ironing is recommended for ironing-oriented reduction.

Tolerances smaller than the material thickness are generally not recommended, since the ironing force will be excessive and tearing of the product may occur even though a process of long tubes' drawing often utilizes clearances of up to 0.9t, or up to 10 percent smaller gaps than the material thickness.

9-4-3 Radius of Drawing Punch and Die

As already mentioned, the radius of the die section should be quite liberal in size. However, too large radii are not desirable either, as they enhance the material's tendency to wrinkle and fold.

The basic recommended sizes of tooling radii for drawing punches and dies are:

First drawing die radius: (6 to 10)t

Redrawing die radius: (6 to 8)t

Drawing punch values differ with the diameter of shell d as follows:

For d = 0.25 to 4.0 in. [6.3 to 100 mm], R_P = (3 to 4)t

For d = 4.0 to 8.0 in. [100 to 200 mm], R_P = (4 to 5)t

For d = above 8.0 in. [200 mm], R_P = (5 to 7)t

The size of the punch radius is further influenced by the depth of the draw, percentage of reduction, and type of metal. For comparison, a chart of the recommended radii for a given thickness of the material is included in Table 9-8.

The continuity of the radius is not required to cover a whole 90° area of the corner. Variations of this portion are possible (see Fig. 9-35).

The radius of the die has a direct influence on the drawability of the material, which it may influence in a positive or negative manner. Since the size of the die radius depends on

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TABLE 9-8 Radii of Drawing Punches and Dies

Stock thickness		Drawing edge radius, punch or die	
in.	mm	in.	mm
0.015–0.018	0.36–0.45	0.156–0.250	4.00–6.35
0.021–0.027	0.50–0.70	0.187–0.281	4.75–7.15
0.031–0.046	0.80–1.2	0.187–0.312	4.75–8.00
0.048–0.062	1.2–1.6	0.250–0.375	6.35–9.50
0.078–0.093	2.0–2.25	0.312–0.437	8.00–11.00
0.109–0.125	2.8–3.5	0.343–0.468	8.70–12.00

its relationship to the thickness of the drawn material, it subsequently suggests that with a thicker blank, the influence of the die radius diminishes (Fig. 9-36).

Friction, as encountered in the drawing process, consists of two segments:

- *Friction between the drawing punch and the material.* This type of friction utilizes a portion of the drawing force toward the material and as such, it decreases radial tension, decreases the coefficient of friction, and allows for deeper draws.
- *Friction between the drawn material and the die.* This type of friction acts quite the opposite way, causing an increase in radial tension, which, in turn, causes a subsequent rise of the coefficient of friction with decrease in the attainable height of the drawn part.

For these reasons, the edge of the drawing punch is sometimes purposely roughened up to the point where radial ridges are implemented. These not only help in increasing the friction between the punch and the material; they additionally aid in removing the trapped air from the area between the punch and the drawn shell.

Single-piece drawing punches are being utilized for drawing of small diameter cylinders; larger diameters, from 4 in. [100 mm] up, benefit from segmented punches, as shown in Fig. 9-37. Here the clearance space between the insert and the body of a punch can either be kept as shown, or be transferred to the (outer) circumferential portion of the tool, in which case the central sections will butt against each other, with no gap in between. However, for the reasons of maintenance, considering that a gap on the outer surface of the punch may suffer from dirt and lubricant entrapment, the clearance is most often best if kept in the middle as shown.

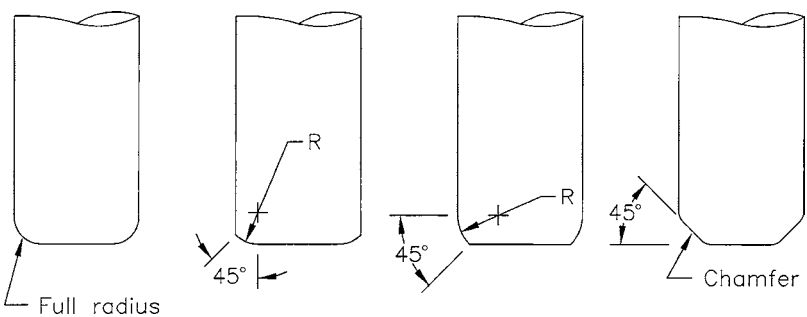

FIGURE 9-35 Drawing punch edge shapes.

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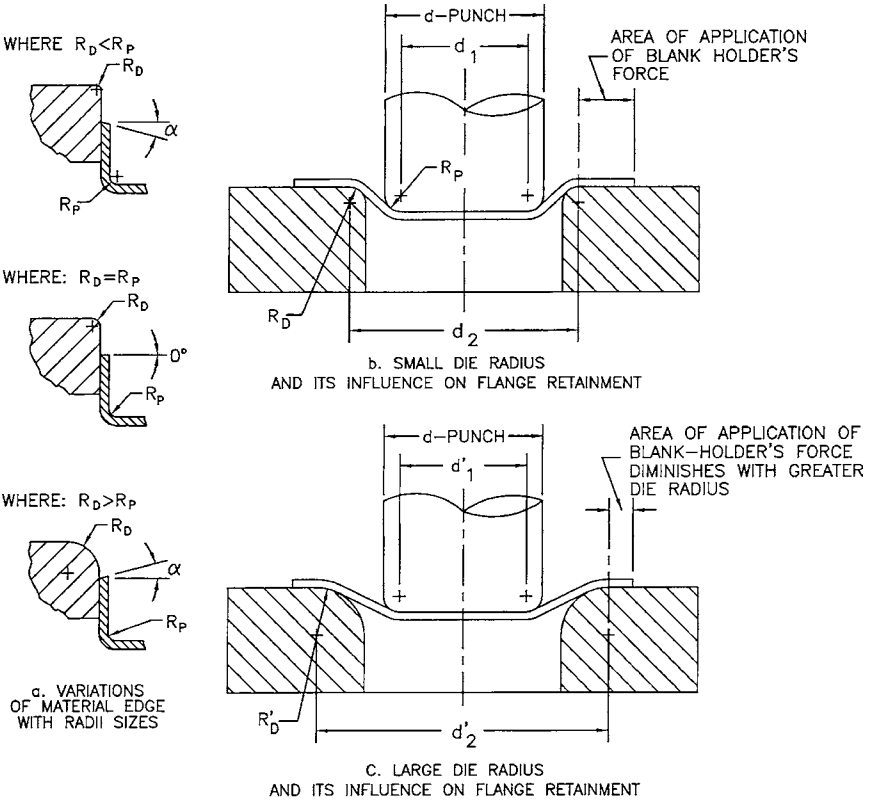

FIGURE 9-36 Size of tooling radii in drawing process. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by CVUT, Brno, Czech Republic.

The die surface finish should be exactly the opposite from that of the punch: highly polished, made of high wear-resistance material, perfectly rounded even where chamfered (the edges of the chamfer must be rounded and absolutely smooth), with no nicks or dents in its drawing surface. The direction of finishing operations should not be circular, if possible, but the final polish should go across the die radius, so that the drawn material would not get entrapped in the miniature circumferential ridges left there by the finishing tooling. Size of the die radius, if enlarged, decreases some frictional forces and enhances the drawing process, so that greater depths may be attained in one operation. However, with the enlargement of the radius, the area of the flange under the blankholder diminishes, affecting the stability of the drawing operation, with possible emergence of defects. Too small a die radius further causes tearing of the stock, while too large a radius may be the reason behind the appearance of wrinkles.

If an angle is selected in replacement of the die radius, it should be made equal to 60° off the horizontal for a simple push-through die. Such a type of die should be used only for a stock thickness greater than 0.062 in. [1.5 mm] or for shells smaller than 3.25 in. [82 mm] diameter (see Figs. 9-38 and 9-39).

Angular die edge, where used for redrawing of cylindrical shells in a simple push-through die (Fig. 9-40) should be restricted to a stock thickness greater than 0.062 in. [1.5 mm] or to shells smaller than 3.25 in. [82 mm] diameter.

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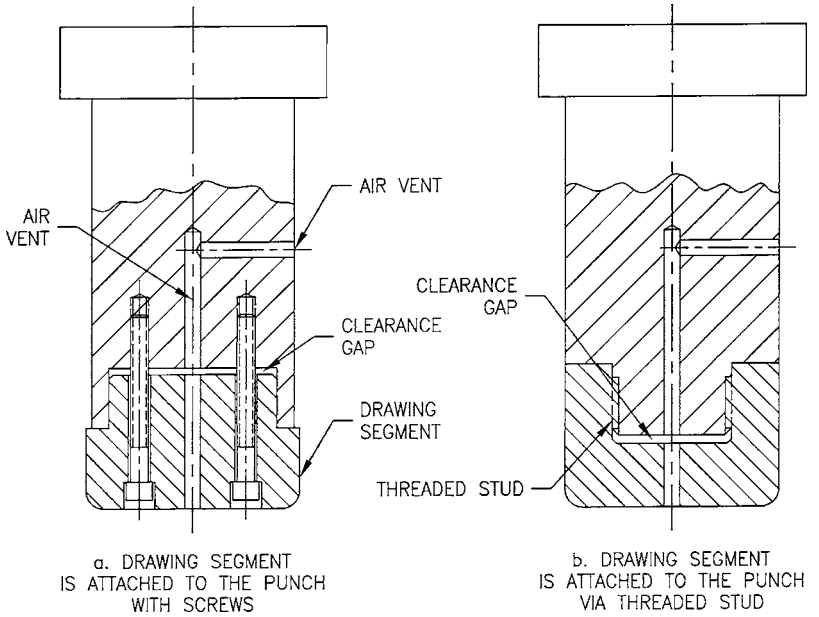
AIR VENT
AIR VENT
CLEARANCE GAP
DRAWING SEGMENT
CLEARANCE GAP
THREADED STUD
a. DRAWING SEGMENT IS ATTACHED TO THE PUNCH WITH SCREWS
b. DRAWING SEGMENT IS ATTACHED TO THE PUNCH VIA THREADED STUD

FIGURE 9-37 Drawing punches made of segments.

A beveled drawing die for redrawing, utilizing an inner blankholder (shown in Fig. 9-41), may be used for all material thicknesses. The angle, however, may vary (see Table 9-9).

A method of determining the size of corner angle and bottom radius for redrawing dies (shown in Fig. 9-42) bases the size of radii on the material thickness as well. Here a shell requiring two preliminary drawing operations and a final finishing draw is shown. Where such a shell will need more than this many preliminary drawing passes, the same procedure for corner angle layout should be followed.

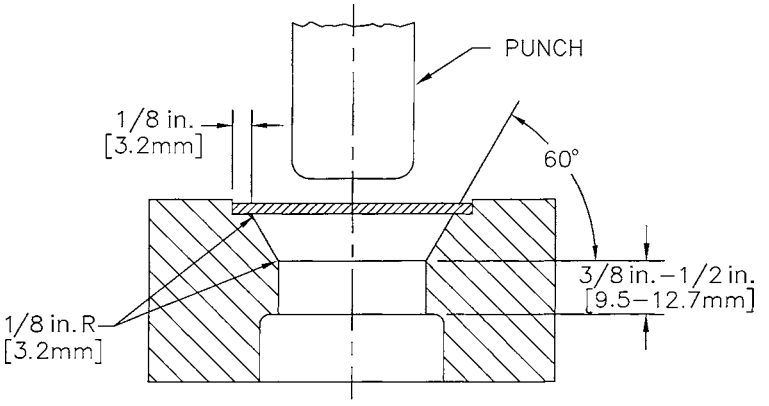

FIGURE 9-38 Cross-section of beveled drawing surface of a simple, push-through drawing die (dimensions are approximate).

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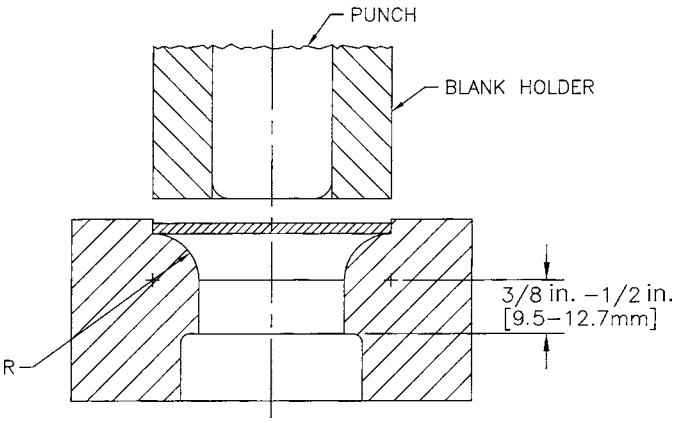

FIGURE 9-39 Cross-section of radiused drawing surface of a simple, push-through drawing die (dimensions are approximate).

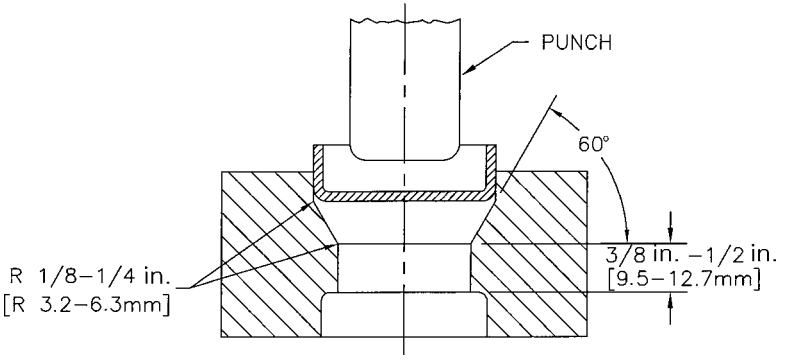

FIGURE 9-40 Cross-section of beveled drawing surface of a simple, push-through redrawing die (dimensions are approximate).

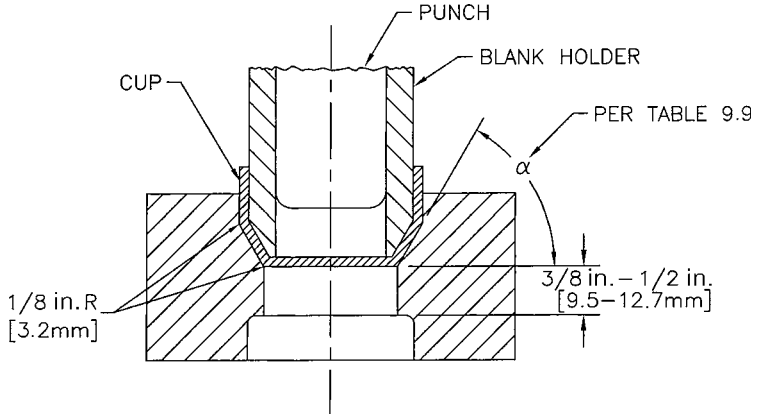

FIGURE 9-41 Cross-section of beveled drawing surface of a simple, push-through redrawing die with inner blankholder (dimensions are approximate).

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TABLE 9-9 Angle of Drawing Surface and Its Variation with Stock Thickness. Redrawing of Cylindrical Shells Utilizing Inner blankholder

Stock thickness		Angle α value, degrees
in.	mm	
0.012–0.031	0.32–0.8	30
0.031–0.062	0.8–1.6	40
Over 0.062	Over 1.6	45

A mathematical method of evaluation of the proper size of the first drawing die radius follows.

$$R_{\text{die–First}} = \sqrt{0.8(D_0 - d)t_0} \tag{9-26a}$$

where D_0 = blank diameter
d = inner diameter of shell
t_0 = thickness of blank

CSN 22 7301 recommends using the radius size of (6 to 10)t for a single-pass drawing operation.

For all redrawing dies, the above formula becomes

$$R_{D\text{–redraw}} = \frac{d_1 - d_2}{2} - t_0 \tag{9-26b}$$

where d_1 is the shell diameter before redrawing and d_2 is the anticipated shell diameter after redrawing.

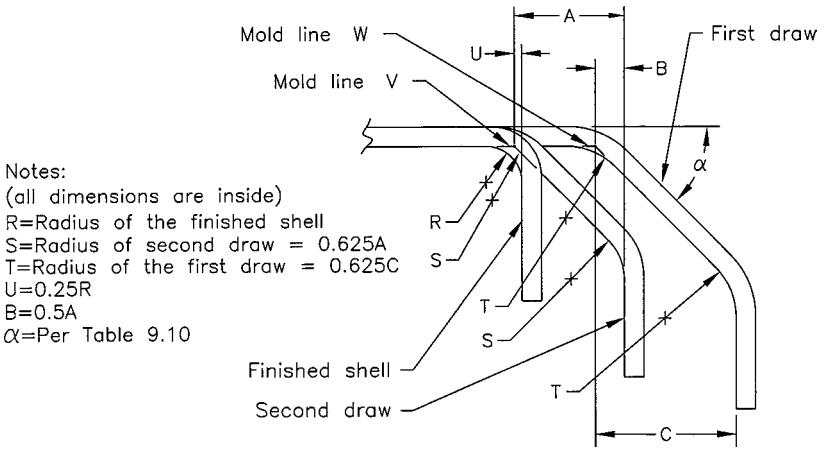

FIGURE 9-42 Dimensional relationship of redrawn cylindrical shells (dimensions are approximate).

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TABLE 9-10 Angles of Redrawn Cylindrical Shells and Their Variation with Stock Thickness

Stock thickness		Angle α value, degrees
in.	mm	
0.012–0.031	0.32–0.8	30
0.031–0.062	0.8–1.6	40
Over 0.062	Over 1.6	45
Stainless steel, all thicknesses		45

The relationship of the blank thickness and diameter may also be expressed by the equation

$$\Delta t = \frac{100 t_0}{D_0} \tag{9-27}$$

where Δt = difference in thickness
t_0 = blank thickness
D_0 = blank diameter

If the result is $\Delta t > 2$, a blankholder is not necessary.
If $\Delta t < 1.5$, a blankholder must be used.
If Δt is between 1.5 and 2, the decision is not substantiated and has to be evaluated on the basis of actual test.

Some recommended values of drawing die radii are shown in Fig. 9-43. Different hatched areas of this graph are to be used for the following applications:

Area *a* = for flanged shells

Area *b* = shells without flange

Area *c* = shells having a frictional insert (such as draw beads)

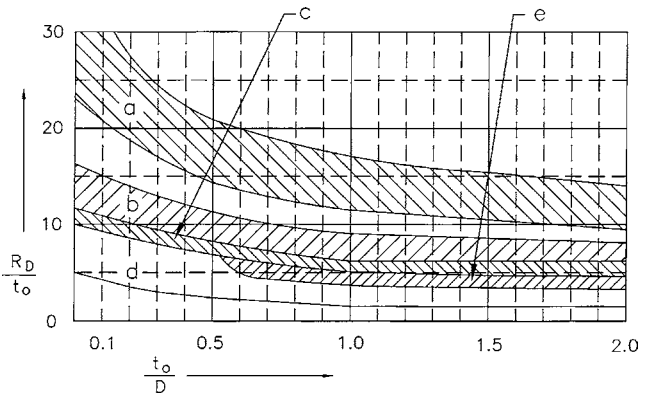

FIGURE 9-43 Die radii values. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

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Area *d* = a continuation of area *b*

Area *e* = for progressive tooling

This suggests that thin metals may be drawn without a blankholder only where the drawn shell is shallow and the coefficient *M* of severity of draw is large.

Additional methods of evaluation of the size and shape of the drawing die edge may be found in Sec. 9-4-4. The *shaped die edge* and *tractrix curve edge* described there may be applied to drawing of regular cylindrical shells as well as to thick-walled cylinders.

9-4-4 Shape of Drawing Dies' Edges

Shape of the edge of the drawing die is based on various evaluations, which had to take into account the factors such as:

- Mechanical properties of the drawn material
- Thickness of the drawn material
- Which drawing operation, first or subsequent
- Type of the drawing die arrangement
- Usage of blankholder
- Amount of press strokes per minute

With regard to the results of the above evaluations, there is a further choice of drawing die edge. As shown in Fig. 9-44, there are at least three different choices available.

9-4-4-1 Huygens' Tractrix Curve. This type of drawing edge begins at a point *A* (Fig. 9-45*a*) and is further developed by an evolving catenary. This type of drawing edge construction method allows for the use of the smallest drawing pressures, while attaining the best severity of draw coefficient of 0.35. The tractrix curve is produced by a continuous tangential contact of the drawn part's edge with the die.

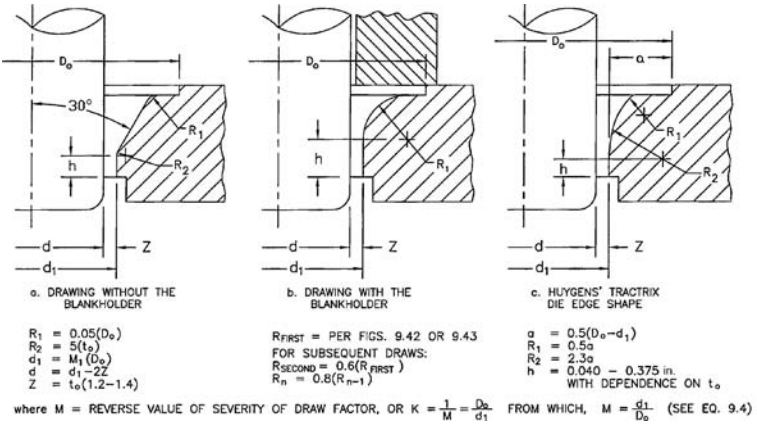
D_o
30°
R_1
R_2
h
d
d_1
Z
a. DRAWING WITHOUT THE BLANKHOLDER
$R_1 = 0.05(D_o)$
$R_2 = 5(t_o)$
$d_1 = M_1(D_o)$
$d = d_1 - 2Z$
$Z = t_o(1.2-1.4)$
b. DRAWING WITH THE BLANKHOLDER
R_{FIRST} = PER FIGS. 9.42 OR 9.43
FOR SUBSEQUENT DRAWS:
$R_{SECOND} = 0.6(R_{FIRST})$
$R_n = 0.8(R_{n-1})$
a
c. HUYGENS' TRACTRIX DIE EDGE SHAPE
$a = 0.5(D_o - d_1)$
$R_1 = 0.5a$
$R_2 = 2.3a$
h = 0.040 – 0.375 in. WITH DEPENDENCE ON t_o
where M = REVERSE VALUE OF SEVERITY OF DRAW FACTOR, OR $K = \frac{1}{M} = \frac{D_o}{d_1}$ FROM WHICH, $M = \frac{d_1}{D_o}$ (SEE EQ. 9.4)

FIGURE 9-44 Types of drawing die edges. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

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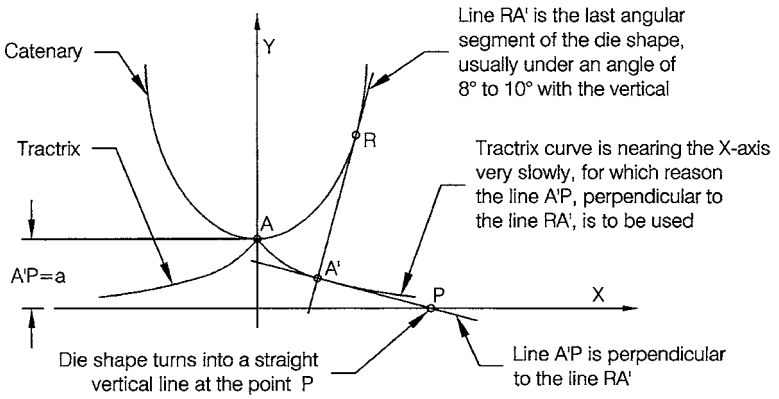
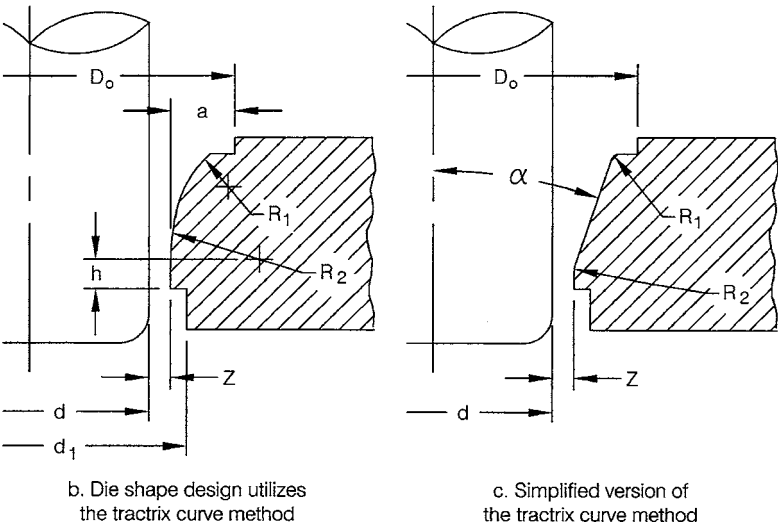

Catenary
Y
Line RA' is the last angular segment of the die shape, usually under an angle of 8° to 10° with the vertical
Tractrix
R
Tractrix curve is nearing the X-axis very slowly, for which reason the line A'P, perpendicular to the line RA', is to be used
A
A'P=a
A'
P
X
Die shape turns into a straight vertical line at the point P
Line A'P is perpendicular to the line RA'

a. Die shape development using the tractrix curve method



b. Die shape design utilizes the tractrix curve method

c. Simplified version of the tractrix curve method

FIGURE 9-45 Drawing edge development using Huygens' tractrix curve. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

The equation form of the tractrix curve is

$$x = a \ln \frac{a + \sqrt{a^2 - y^2}}{y} - \sqrt{a^2 - y^2} \tag{9-28}$$

The tractrix's asymptote is the axis x, with the axis of rotation being y and the radius of the curve being

$$R = a \cot \frac{x}{y} \tag{9-29}$$

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Geometry of the drawing die is shown in Fig. 9-45*b*. The radius here consists of two combined radii R_1 and R_2, out of which the first R_1 is the line of the tractrix. However, since the tractrix curve is nearing the x axis, which actually is a centerline of the drawn part, only very slowly, a great height of such a die would be necessary, with a subsequent extended stroke of the press. For that reason, a tangent under an angle of $\alpha = 8$ to 10° with the vertical is attached to the end of the tractrix curve.

Practical parameters for this type of evaluation are as shown below:

$$a = \frac{D_0 - d_1}{2}$$

$$R_1 = 0.5a$$

$$R_2 = 2.3a$$

$$d_1 = d + 2z$$

$$z = (1.2 - 1.4)t_0$$

h = between 0.040 and 0.400 in. [10 and 100 mm], depending on the thickness of the blank

Since the actual manufacture of such a complex curve may sometimes pose a problem, a simplified shape of the drawing die, shown in Fig. 9-45*c* has been derived. Here the tractrix line is replaced by a straight angular segment, usually at angle $\alpha = 30°$ with the vertical. Other values may be used as

$$R_1 = 0.05\ D_0$$

$$R_2 = 5t_0$$

$$d = M(D_0)$$

where M is the coefficient of severity of draw.

The radius of the drawing punch should be made equal to the radius of the drawing die, or $R_{\text{punch}} = R_{\text{die}}$. For progressive redrawing operations, the edge of the punch is often chamfered at 35 to 45°.

The radius of the last redrawing punch of a sequence should be a minimum of (3 to 7)t0, with the following variations for a given thickness of blank:

3 to $4t_0$, for blanks of ø0.40 to 4.00 in. [10 to 100 mm]

4 to $5t_0$, for blanks of ø4.00 to 8.00 in. [100 to 200 mm]

5 to $7t_0$, for blanks of ø8.00 in. [200 mm] and up

The surface of the drawing punch must be smooth in order not to impair the drawing process in any way. Air vents are vital to the outcome as well.

9-4-4-2 Pelczinski's Development. Another technique of solving the drawing punch and die relationship is Pelczinski's method, which forms the die radius in such a fashion that the point of contact between the die and the drawn part is always restricted to the edge of the radius. Such a die edge modification is arrived at graphically, with the drawing operation divided into segments and with each of the segments evaluated separately for the location of the edge, as seen in Fig. 9-46.

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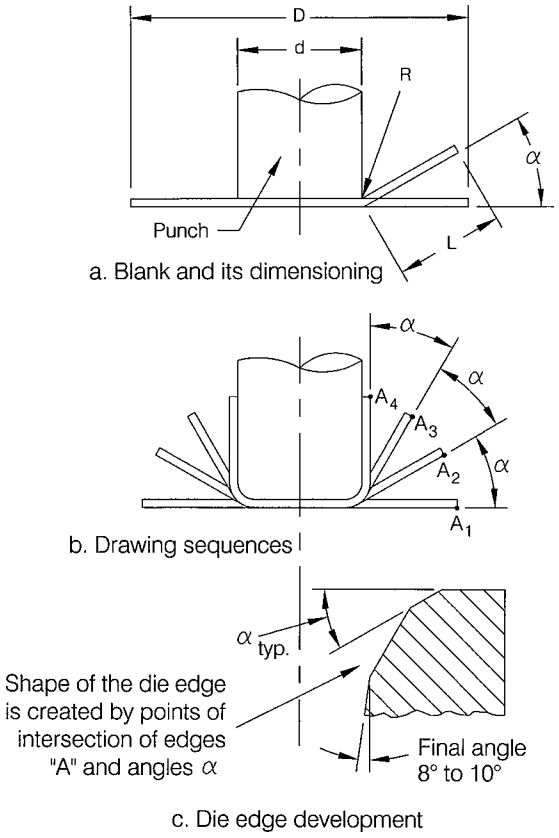

FIGURE 9-46 Pelczinski's method of drawing edge development.

This theory considers the wall thickness of the drawn part constant, in which case Eq. (9-19) applies:

$$\frac{D^2 - d^2}{4} = \alpha R d\pi + 2\pi R^2 (L - \cos\alpha) + L\pi(d + 2R\ \sin\alpha + L\ \cos\alpha) \tag{9-30}$$

The result helps to determine additional dimensions involved in this evaluation as

$$\cos\alpha = \frac{R^2 - \left(\frac{d}{2}\right)^2}{\left(\frac{D_0}{2}\right)^2 - \left(\frac{d}{2}\right)^2} \tag{9-31}$$

where all values are from Fig. 9-46.

The configuration of the die radius is shown in Fig. 9-46*b*, where all points corresponding with various locations of the bent-up flange are shown. The final angle is the continuation of the last inclined surface, usually in the vicinity of 8 to 10° with the vertical.

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The drawing force diagram, if drawn, will not show any great deviation from the constant until the shell arrives at the area of 8 to 10° draft, at which point there will be an increase in the drawing pressure. Such a curve, if compared to that created by a large-radiused die, will clearly show a decreased demand for drawing pressure.

9-4-5 Trimming of Drawn Shells

There are several ways to trim a simple drawn shell, with or without a flange. The most often used pinch-trimming method was already shown in the Fig. 3-32. A newer method using a Brehm's Shimmy Die®, was shown previously in Figs. 3-33 through 3-36.

In Fig. 9-47, the values to be used when designing the pinch-trimming station are given. Notice that the trim section is added to the assembly as a separate insert, which allows for sharpening of the cutting edge, or for its exchange.

Another approach to pinch trimming of angular flanges is presented in Fig. 9-48. The two methods shown can trim the parts by placing the undercut either downward, or up.

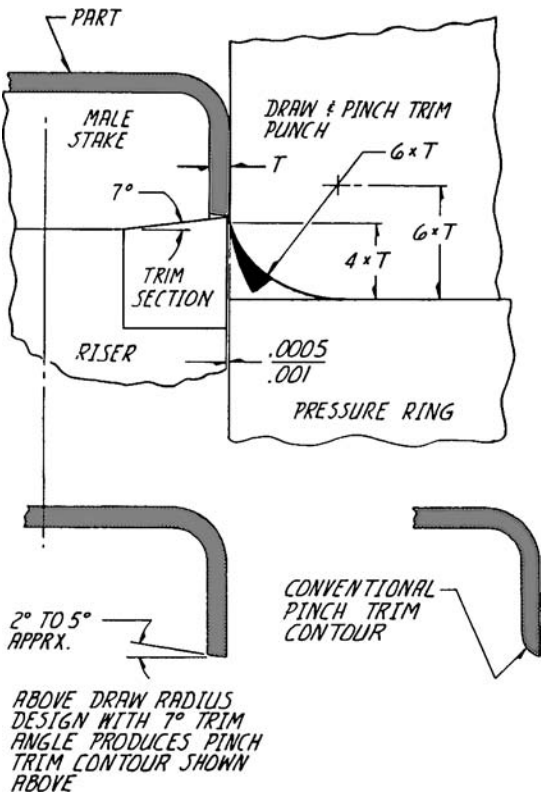

FIGURE 9-47 Die design for removing pinch trim radius. (*From: Practical Aids For Experienced Die Engineer, Die Designer, and Die Maker, 1980. Reprinted with permission from Arntech Publishers, Jeffersontown, KY.*)

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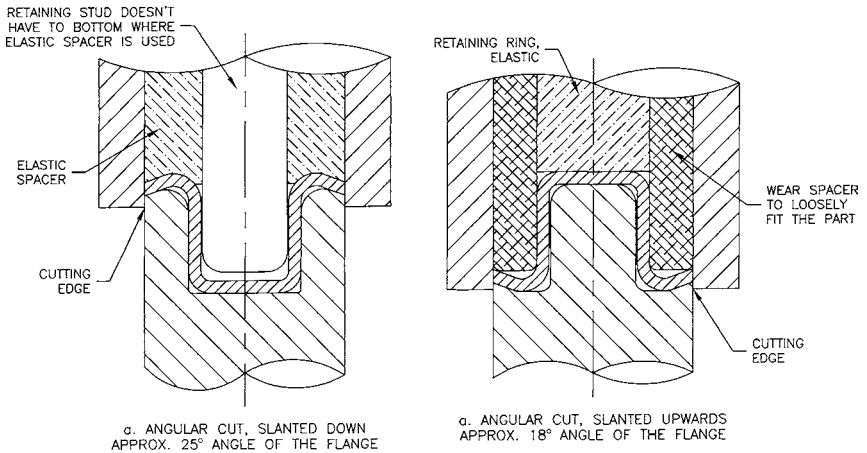
RETAINING STUD DOESN'T HAVE TO BOTTOM WHERE ELASTIC SPACER IS USED
ELASTIC SPACER
CUTTING EDGE
a. ANGULAR CUT, SLANTED DOWN APPROX. 25° ANGLE OF THE FLANGE
RETAINING RING, ELASTIC
WEAR SPACER TO LOOSELY FIT THE PART
CUTTING EDGE
a. ANGULAR CUT, SLANTED UPWARDS APPROX. 18° ANGLE OF THE FLANGE

FIGURE 9-48 Pinch trimming of shells with an angular flange.

9-4-6 Air Vents

No drawing operation can be successful if appropriate air vents are missing from the body of a punch, as a drawn part has a tendency to stick to the punch around which it is wrapped, and remain there, as retained by the force of vacuum thus created.

Air vents serve a dual purpose in the drawing operation (Figs. 9-49 and 9-50). During the drawing cycle, they eliminate the air entrapped between the face of the punch and the bottom of the drawn shell. At the end of drawing, they permit the air to reenter the space between the punch and the part, to aid in the stripping of the latter. In the absence of vents, the drawn shell would either collapse or be impossible to strip off the punch.

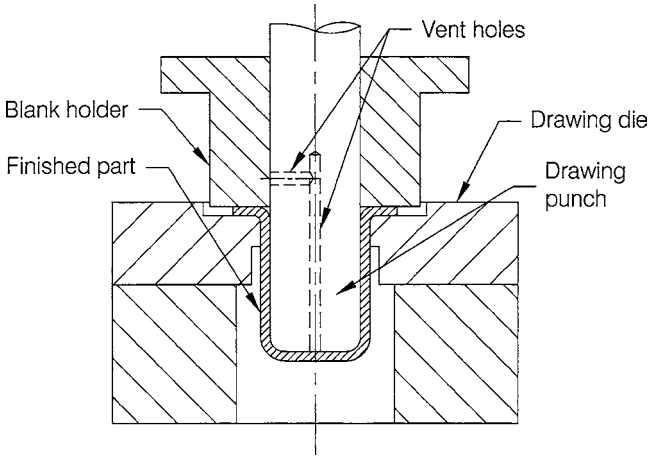

FIGURE 9-49 Drawing punch showing vent holes.

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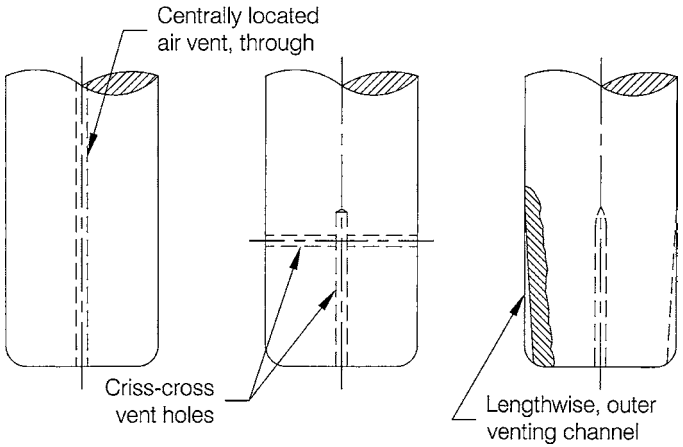

FIGURE 9-50 Air vents in tooling.

Air vents must be protected from any dirt and lubricants, which are so abundant in the drawing operation. For this reason, air vents should be placed where the least of contamination can be expected. With complex parts, vent openings should be planned in such a way, as to guide the air from the deepest areas of the drawn part. Preferably, vents should be placed on the opposite side of sections, which will be trimmed off later on.

Practical air vent diameters for tooling with a single air vent opening are as shown in Table 9-11. For cylindrical shell, a single air vent will suffice most of the time. However, where noncircular shapes are drawn, more than one air vent should be considered.

9-4-7 Drawing Inserts

Drawing dies for large production runs may be combined from two or more segments instead of a single block, complex in shape. Instead of carving and finishing the drawing opening in a block, a press-in ring, fabricated to the exact shape may be used (Fig. 9-51 and 9-52). Such a ring can be replaced when necessary with no impairment to the remainder of the block and with minimum downtime.

TABLE 9-11 Air Vent Diameters

Punch diam., in. (mm)	Air-vent diam., in. (mm)
Up to 2 (51)	0.188 (4.78)
2 to 4 (51 to 102)	0.250 (6.35)
4 to 8 (102 to 203)	0.312 (7.92)
Over 8 (203)	0.375 (9.52)

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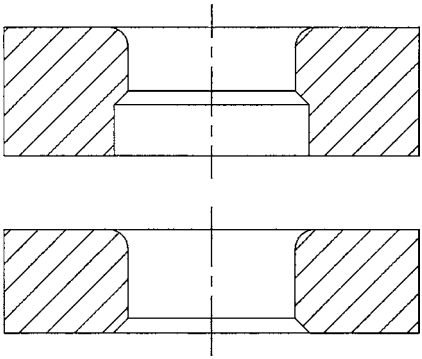

FIGURE 9-51 Drawing inserts.

9-5 DRAWING OF THICK-WALLED CYLINDERS

Drawing of thicker materials is slightly different from drawing of thin-walled shells. First of all, these parts often do not need a blankholder, as the thickness of material prevents the blank from collapsing under the tangential pressure. Single-action tooling may be utilized for production, which brings the cost of the die down. The disadvantage is the more demanding construction of the die and a greater press stroke.

The radius of the drawing die is of utmost importance here, for the process depends on a low coefficient of friction. One way to achieve this is to make the die radius of such a size and shape that it continuously pushes the drawn material against the punch.

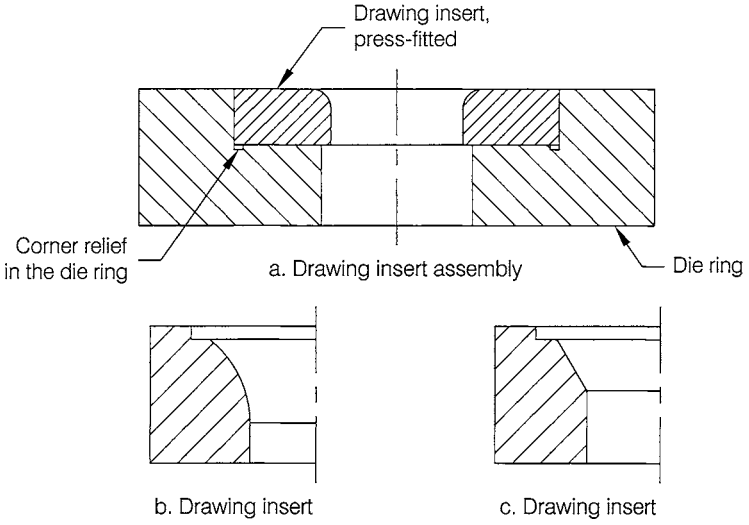

FIGURE 9-52 Drawing inserts and their application.

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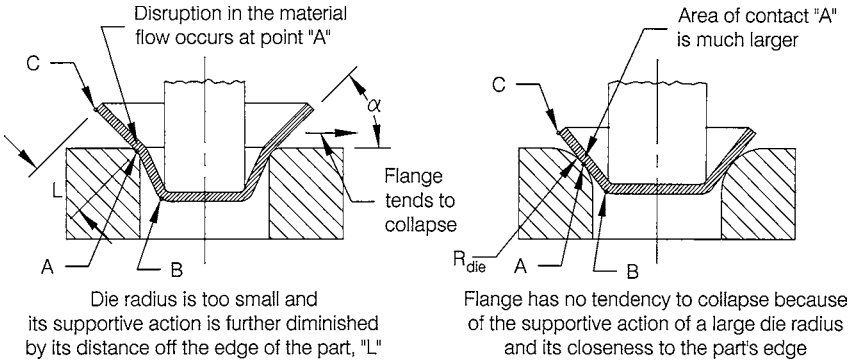

FIGURE 9-53 Drawing of thick-walled cylinders. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

In Fig. 9-53, the difference between small and large radius is shown pictorially. With a greater than necessary distance between the point of support *A* and the edge of the blank, an additional bend in the flange is created. Such a bend not only increases the need of drawing pressure, it also exposes the material to wrinkling within the area of flange.

9-6 DRAWING OF SQUARE OR RECTANGULAR SHAPES

When drawing a square or rectangular shape, the first that must be evaluated is the depth of the draw. If the depth of a part is not excessively deep, perhaps the same product may be obtained by a much easier manufacturing method, such as stretching. However, where greater depths are involved, the drawing process must be utilized.

Drawing of box-type objects is susceptible to various stresses within the material, which are far from being evenly distributed around the edge of a die. Plastic deformation at the level of the flange is present within the area of partial-cylindrical corners, as with round cylindrical shells. The sides of a box, which theoretically should contain only a radial tension, such as that imposed by simple bending, are actually quite stressed. This is due to the stress step between the two stress differences, that of the side and that of the corner area, the influence of which is considerable.

Shown in Fig. 9-54 is a sketch of a drawn cylindrical shape (Fig. 9-54*a*) and a box-type part (Fig. 9-54*b*). Main dimensions R_b, R_d, R_c, h, and t_0 are the same for both products. In both cases, the two-dimensional stress within the flange (σ_1 tension, σ_3 compression) is applicable. With the cylindrical shape, the tension is equally dispersed throughout the circumference, and its direction and value are consistent all around. The box-type drawn part suffers from inequalities between these influences, the directions and values of which change as they approach the corner: their quantity diminishes, and their direction is diverted from their radial course toward the adjacent sides (see Fig. 9-54*c*).

The tension contained in the drawn body of each shell is directed along a single axis. However, in a square shell, its value reaches the upper limit in the corner, with decreasing tendencies along the straight sides.

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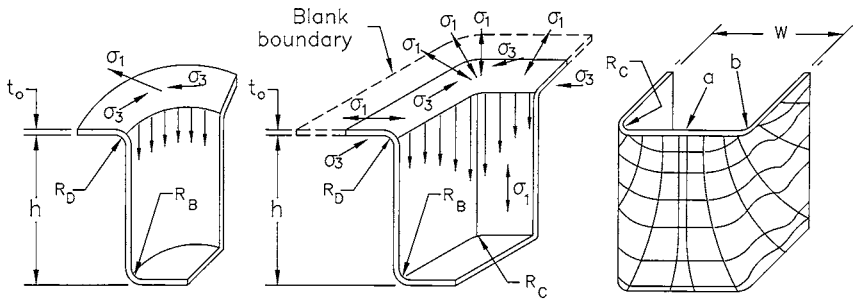

a. Forces within a cylindrical shell caused by drawing

b. Forces within a rectangular or square box, caused by drawing

c. Effects of structural deformation of a square or rectangular drawn box

FIGURE 9-54 Deformation of a drawn shapes. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

Figure 9-54*c* depicts the lines of deformation within the part. As can be seen, the straight sides of the box suffer from certain bending influences, accompanied by complex deformations, which produce a compression tendency of the circumference of the part and an extension of the area of the bottom edge. Therefore, the widely accepted claim that the drawing of a square or rectangular shape is restricted to the corner areas while the rest of the shape alteration is due to simple bending, is proven inaccurate.

Approximate values of the deformation, assessed in the middle of the upper edge (point *a*) and around the corner radius (point *b*) are recorded in Table 9-12. Values of the cylindrical shape are included for comparison.

With regard to the depth of draw, the tangential flow may reach quite high levels, exceeding columnar (buckling) limits of the drawn material. This may cause an appearance of wrinkles within the drawn body of the part. Columnar limits depend on the thickness of the wall and geometry of the die radius, whereas tangential stress is related to the radius of the corner of a part, plus wall thickness, and the depth of draw, or *t*/*d*.

Alignment of the two different stress situations, such as those within the corner and straight side of a part, can be solved by the alteration of the part's geometry and by a partial decrease of the drawing space between the punch and die in straight areas. Another helpful solution is the installation of draw beads, which slow down the drawing process of these sections. An application of draw beads in shown in Fig. 9-55.

TABLE 9-12 Amount of Deformation Per Drawn Height

	Value of deformation		
	Rectangular shape		
Height of drawn shape	Point a	Point b	Cylindrical shape
h = W	25–30	45–50	55
h = 0.5W	15–20	30–46	40
h = 0.3W	5–8	15–30	31

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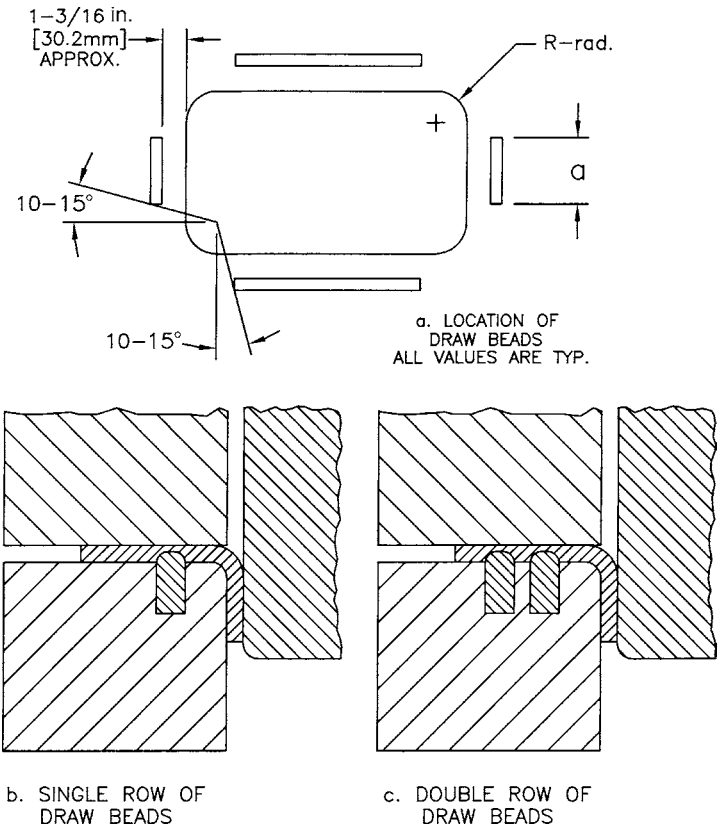

FIGURE 9-55 Draw beads in rectangular or square parts' drawing.

Draw beads may be positioned on the die block, where their distance off the drawing edge should be approximately 1.187 in. (30.2 mm). They may be added as a single row, or doubled, with a maximum of three rows. The exact number of draw beads per side of the rectangular or square box is usually determined on the basis of testing.

Naturally, the width of a flange is of importance in such drawing, and an exact blank layout of the part is essential for the success of the drawing operation.

To calculate widths and lengths of the straight, bent-up portions of a box-type shell, the formula for 90° bends may be used (see Sec. 8-6-2, Table 8-8).

9-6-1 Clearance Between Punch and Die

For drawing of rectangular or square shells in one operation, the clearance between the punch and die should be equal to the thickness of the drawn material. This situation is sometimes referred to as "metal-to-metal."

A slightly larger than metal thickness corner clearance will greatly reduce the drawing pressure while reducing the strain on the shell as well.

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TABLE 9-13 Clearance Between the First Drawing Punch and Die for Square Or Rectangular Shells

Material	Per-side clearance between punch and die
Aluminum	1.25t
Steel, deep drawing	(1.1 to 1.2)t
Stainless steel	(1.75 to 2.5)t

*t = stock thickness.

Shells that require more than one drawing operation should use a clearance chosen with regard for the material being drawn. Basic guidelines for the proper choice of such a clearance are included in Table 9-13.

9-6-2 Drawing Radii

Drawing of box-type shapes usually cannot be performed in one drawing pass, because the depth of the draw may be quite restrictive. However, using two successive dies may create another problem, especially where drawing steel material. The drawing pressure, being applied twice in succession to the corner areas, produces considerable stresses within these sections of the part. The sides of a box, previously often considered to be nothing but flat, bent-up sections, are actually vastly affected by the variation in the volume and orientation of stresses caused by the sudden breakage in the continuity of the shape.

Deformation, which affects the sides of the box, is directed toward the corner areas, making these susceptible to greater than usual wear, with the material of tooling being literally eaten away. This condition produces an increase of the gap between the tooling, with ensuing thickening of the drawn material in those sections. Often the corners of such boxes are so congested and strain-hardened that their condition impairs the second drawing process and annealing must be administered in between.

The relationship of two successive dies drawing a square or rectangular shell may be observed from Fig. 9-56.

In the figure, A = corner radii of the finished shell
$B = 5A$
S = approximately 0.125 in. [3.2 mm] to serve as a drawing edge
$T = 3A$ (where A is less than 0.5 in. [12.7 mm]), or 0.75 in. [19.0 mm] (where A is larger than 0.5 in.)
C = bottom radii of finished shell
$D = T + 0.25C$

The size of the drawn box corner radii may be figured with regard to the value of severity of draw M, or

$$M = \frac{2R_{\text{corner}}}{D} \tag{9-32}$$

Values of the coefficient M for the first and second draw are given in Tables 9-14 and 9-15. It may be observed that the longer the straight side portion of the box-type drawn part is the lower a coefficient of severity of draw may be used.

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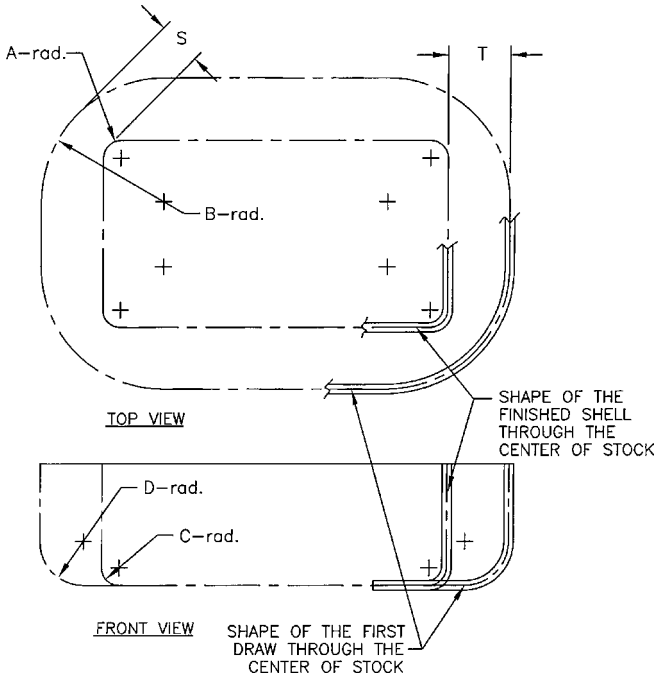

FIGURE 9-56 Blank size and corner radii configuration for square or rectangular shells, produced in two drawing sequences.

TABLE 9-14 Severity of Draw Coefficient *M, Square or Rectangular Shells, First Drawing Pass Only*

	Percentage ratio of thickness to blank diameter 100(t/D)					
Length a^*	0.1–0.3	0.3–0.6	0.6–1.0	1.0–1.5	1.5–2.0	Above 2.0
2R	0.550	0.540	0.520	0.500	0.475	0.450
5R	0.480	0.465	0.450	0.425	0.405	0.380
10R	0.360	0.345	0.330	0.305	0.285	0.260

*(straight length) as per Fig. 9-55

TABLE 9-15 Severity of Draw Coefficient *M, Square or Rectangular Shells, All Redrawing Operations*

	Percentage ratio of thickness to blank diameter 100(t/D)					
Length a^*	0.1–0.3	0.3–0.6	0.6–1.0	1.0–1.5	1.5–2.0	Above 2.0
2R	0.760	0.750	0.740	0.730	0.715	0.700
5R	0.660	0.650	0.640	0.625	0.610	0.590
10R	0.500	0.490	0.475	0.455	0.435	0.415
Last draw	0.880	0.875	0.860	0.855	0.845	0.830

*(straight length) as per Fig. 9-55

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9-6-3 Maximum Depth of a Drawn Shell

The maximum depth of a box-type shell, attained in a single drawing pass, may be determined on the basis of the following variables:

- Type of material and its thickness
- Size of corner radius through the center of stock
- Size of the bottom radius
- Ratio between corner radii and length of straight portions of shortest side
- Width of the flange
- Blank shape and overall size of the shell
- Type of die and press

The size of corner radius is the main factor in determining the depth of a square or rectangular shell. The distance between the corner radii centers should be at least six times the value of a corner radius (see Fig. 9-57). If such a distance should be smaller than 6*R*, the depth of the drawn shell has to be decreased proportionately.

The bottom (bend) radius along the straight sides should be the same size as the corner radius or larger. The size of corner radius in relation to the depth of draw is shown in Table 9-16.

Another way of determining if a given part needs more than one drawing operation is to build a die for the last drawing station and try it.

9-6-4 Approximate Blank Corner Shape for Square or Rectangular Shells Whose Width Exceeds Their Depth

The method of obtaining an approximate shape of the corners of blank for square or rectangular shells is shown in Fig. 9-58. It may be used only for such drawn products whose width exceeds the depth and whose corner radius is equal to the bottom radius.

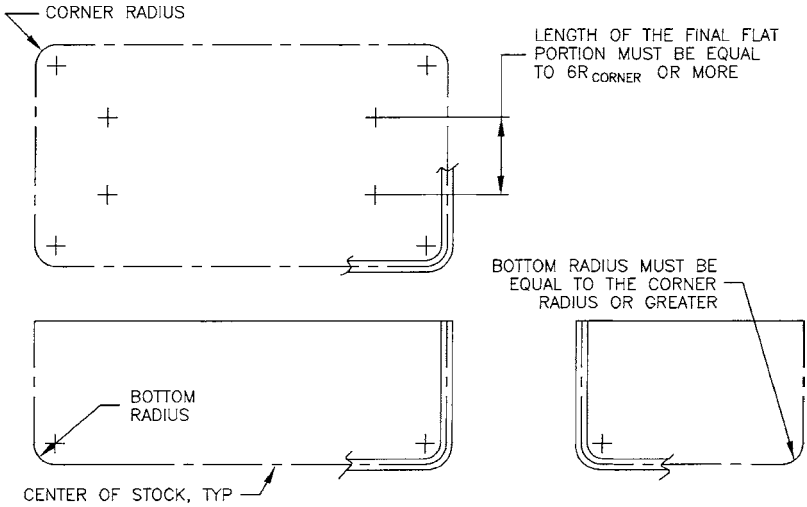
CORNER RADIUS
LENGTH OF THE FINAL FLAT PORTION MUST BE EQUAL TO 6R CORNER OR MORE
BOTTOM RADIUS MUST BE EQUAL TO THE CORNER RADIUS OR GREATER
BOTTOM RADIUS
CENTER OF STOCK, TYP

FIGURE 9-57 Parameters for obtaining a maximum depth in a single drawing operation (square or rectangular shells only).

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TABLE 9-16 Maximum Depth of a Square or Rectangular Shell, Obtainable in a Single Drawing Pass, Using Deep Drawing Stock

Corner radius through center of stock		Maximum drawing depth factor (multiply corner radius by the number below)
in.	mm	
Up to 0.187	Up to 5.00	8
0.187 to 0.375	5.00 to 9.50	7
0.375 to 0.500	9.50 to 12.50	6
0.500 to 0.750	12.50 to 19.00	5
Over 0.750	Over 19.00	4

To find the length and width (in flat) of the sides of the box, bending formulas from Sec. 8-6-2 may be used.

This method of corner development should be used to obtain the shape and size of a trial blank. Formulas for the development of accurate shape of corners cannot be derived, owing to the involvement of too many factors. After drawing of the trial blank, small alterations to the blank outline may be needed.

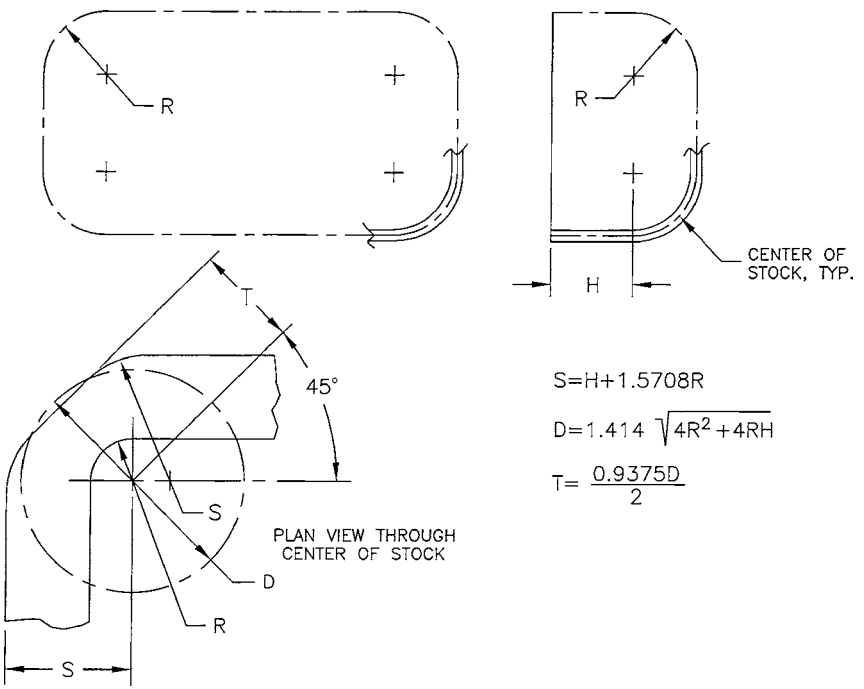

FIGURE 9-58 Approximate size and shape of corners (in flat) for square or rectangular shells.

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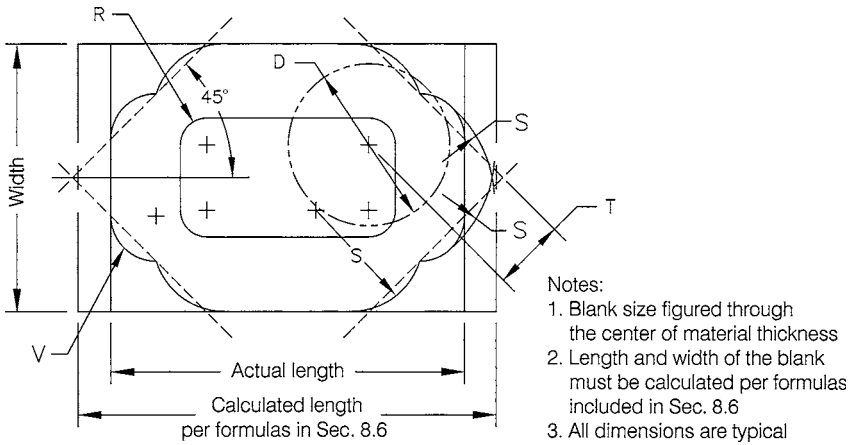

FIGURE 9-59 Graphical method of blank development for square or rectangular shells whose depth is equal to or greater than their width.

9-6-5 Graphical Method of Blank Development for Square or Rectangular Shells Whose Depth is Equal to or Greater Than Their Width

To distribute the metal equally during the drawing process, the calculated length of the blank must be diminished, while the width must be extended in the area of radii *V* and *S*. The amount of decrease in length and increase in width cannot be calculated, as such formulas do not exist. Rather, a sketch shown in Fig. 9-59 should be utilized to graphically construct the shape of the blank. Values for different radii shown should be calculated with the aid of formulas in Figs. 9-58 and 9-60 through 9-63.

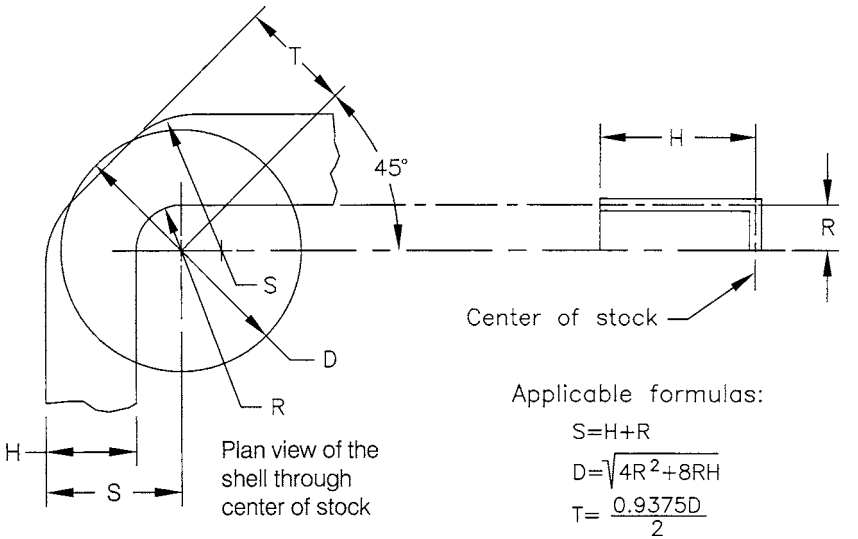

FIGURE 9-60 Approximate blank corner shape for square or rectangular shells of various cross-sections whose width exceeds their depth.

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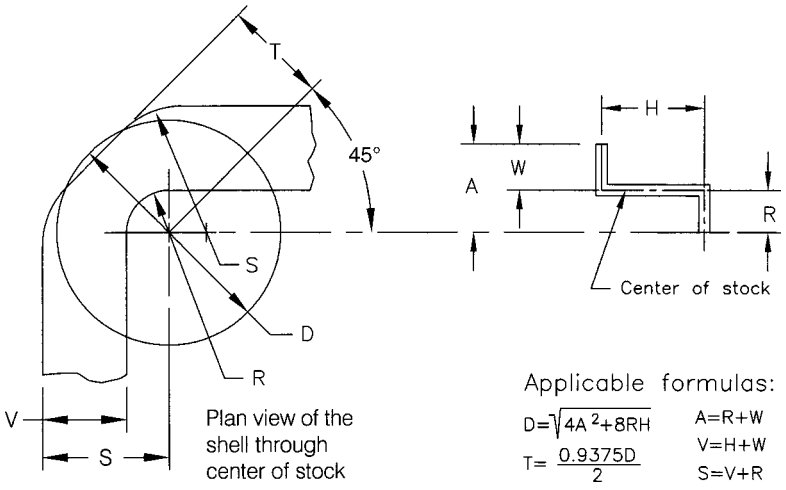

FIGURE 9-61 Approximate blank corner shape for square or rectangular shells of various cross-sections whose width exceeds their depth.

9-6-6 Approximate Blank Corner Shape for Square or Rectangular Shells of Various Cross Sections Whose Width Exceeds Their Depth

The approximate shape of corners of blanks for square or rectangular drawn shells whose width exceeds their depth may be figured with the help of formulas and illustrations shown in Figs. 9-60 through 9-63. Blanks developed with these formulas consider the bottom radius of the shell to be zero. However, since it is nearly impossible to draw shells without

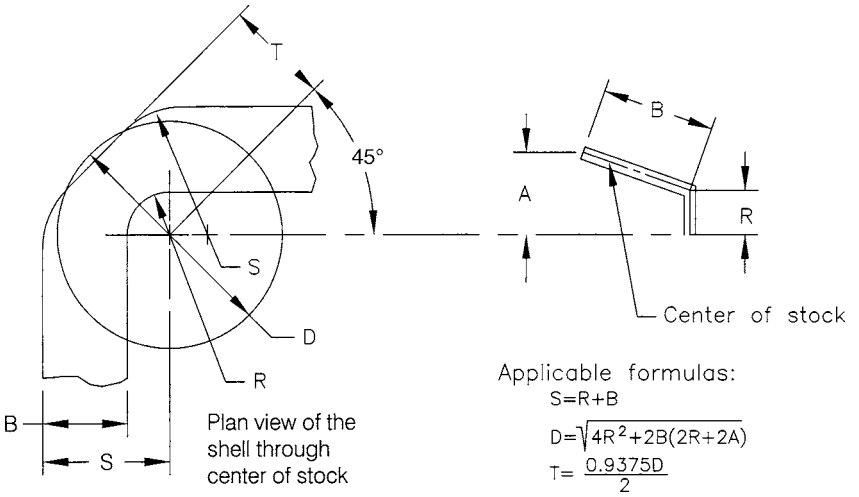

FIGURE 9-62 Approximate blank corner shape for square or rectangular shells of various cross-sections whose width exceeds their depth.

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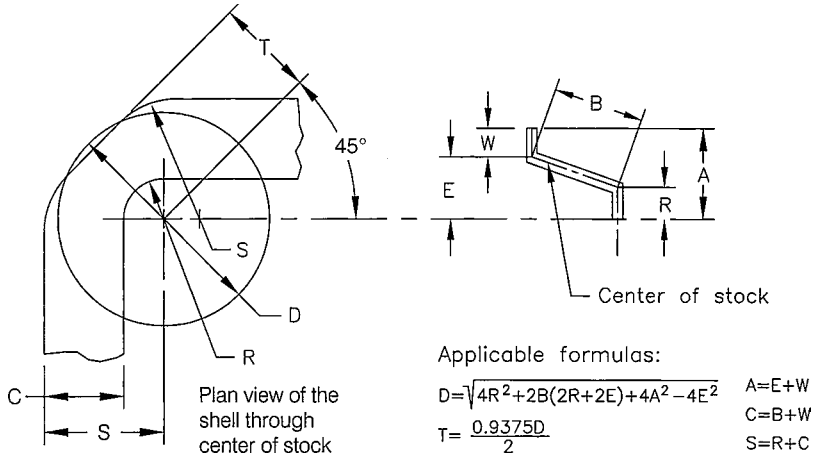

FIGURE 9-63 Approximate blank corner shape for square or rectangular shells of various cross-sections whose width exceeds their depth.

bottom radii, these methods should serve only as guidelines, to quickly and efficiently determine the approximate shape of the trial blank corners.

9-7 DRAWING OF IRREGULAR SHAPES

Drawing of irregular shapes is a complex process that always demands many special considerations. Where cylindrical shells can be drawn the same way at any point of their circumference and where square or rectangular parts have but the difference between the corners and the flat portion to boast about, irregular shapes can be complex along each single line, with height differences adding to the complexity.

Irregular shapes, such as covers, car fenders, and many other such elements, demand a tight control of the dimensional stability of the die, coupled with a proper material flow during drawing. Since production of many of these parts is further complicated by cosmetic requirements pertaining to their exposed surfaces, no defects of any kind are often acceptable on such parts.

For these reasons, the metal flow must be tightly controlled. Where unrestricted flow of material will tend to create wrinkles, draw beads have to be added selectively, where needed. Elsewhere, drawn parts may be cracking due to the flow impairment created by the lock beads in the wrong place. After all, lock beads have the capacity of almost stopping the material flow, which is a dangerous activity.

The designers of irregularly-shaped dies must bear in mind that

- Large punch radius will be merely stretching the material, which will result in the bulk of it being pulled from under the pressure pad (i.e., binder) and from the material already under the punch, in equal amounts.
- Small punch radius will pull the material from under the binder only.

A complex-shaped part may require variations of large and small punch radii along various sections of its shape. In other situations, computer-controlled draw beads may be utilized along with the blankholders's force controlled by the same.

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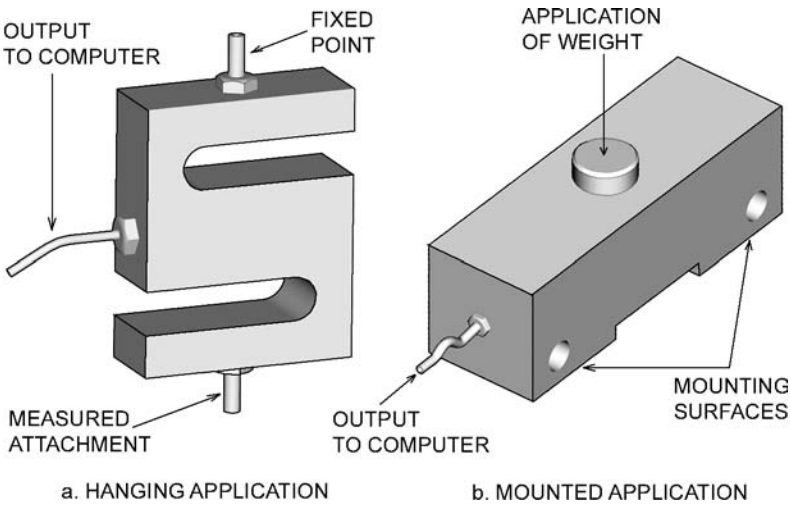

FIGURE 9-64 Load cells.

With computerized controls, the ram of the press can be programmed so that the punch will engage the material at the time the blankholder's pressure is at its highest, for the prevention of wrinkles. As the drawing operation progresses, these values can be manipulated to suit the shape and depth of the drawn part. The blankholder's force at different locations may be monitored by load cells (Fig. 9-64), which are small weighing devices, connected to the computer for the submission of their measurements. The load cell data can be utilized, point-by-point along the press stroke, for manipulation of air or pneumatic cylinders or other devices, which are used to provide the blankholder's pressure. Of considerable advantage is the fact that such computer-generated adjustments and changes are repeatable stroke by stroke, which results in consistent reproducibility of high-quality products.

To locally adjust the blankholder's pressure will not be possible with rigid dies, which we are so much used to, in die design. In such applications, flexible blankholders or multipoint cushion systems must be utilized, where each cushion pin is supported by a separate air or pneumatic cylinder for adjustments (see Fig. 9-65). This way, every pin can be programmed to alter the area of the binder assigned to its span of influence and thus adjust its pressure against the drawn material.

Shown in Fig. 9-66, is the drawing punch that produces an irregularly shaped part. Here the blankholder consists of pyramid-shaped segments made of cast steel, which, when combined with flexible binder and when utilizing the pressure of air or hydraulic pistons, can produce adjustability of the binder pressure segment by segment throughout the whole part.

9-8 REDRAWING OPERATIONS

Redrawing may be divided into two groups:

- Redrawing, where the actions of both punch and die are oriented toward the whole length of the part (Fig. 9-67).
- Redrawing, where the punch exerts its pressure only at a portion of the part, in which case the process is called *reducing and ironing* (Fig. 9-68). Samples of reducing operations are in Fig. 9-69.

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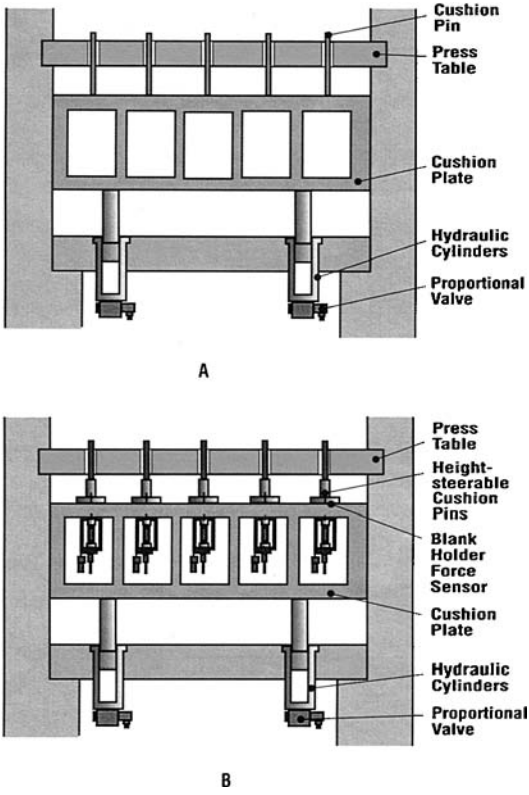

FIGURE 9-65 Hydraulic multipoint cushion system (A) with no separately adjustable cushion pins and; (B) with height-adjustable cushion pins. (*From: The FABRICATOR®, May 2001, page 38, by Klaus Siegert. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

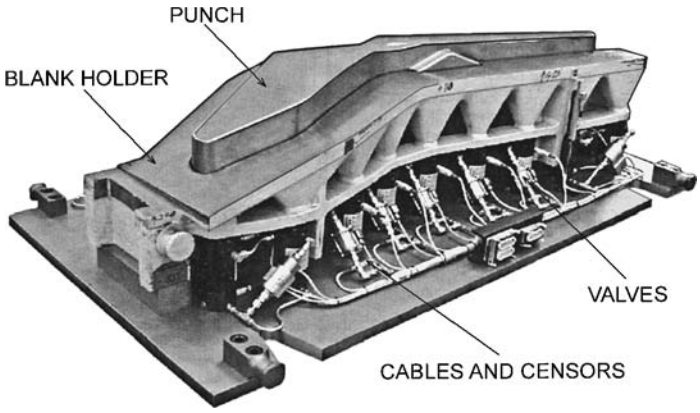

FIGURE 9-66 Draw die for an irregular part, with a segment-elastic blankholder. (*From: The FABRICATOR, May 2001, page 38, by Klaus Siegert. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

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DRAWN PARTS

In redrawing, a part may be drawn into a smaller diameter, or into a greater depth, or thinner wall, or a different cross-sectional shape. Some parts are reverse-drawn, which means the drawing operation progresses in the opposite direction to that of the previous drawing operation, as shown in Fig. 9-70.

Redrawing with no reduction in wall thickness is also called *sinking*; redrawing with subsequent reduction of the wall thickness is ironing (Fig. 9-68). Reducing affects mainly the contour of the part and it additionally goes under other names, such as necking, tapering, or closing.

9-8-1 Drawing Inside Out, or Reverse Drawing

Reversal of the drawing process is utilized for redrawing of existing shells, where greater elongation of the part is desired, while eliminating subsequent drawing operations, needed otherwise. This is achieved by doubly overcoming the material's elastic limit during the two drawing passes, each opposite the other.

Another advantage of inside-out redrawing is the avoidance of wrinkles, as well as an enhanced dimensional stability of the shell. Reverse drawing subjects the formed material to an enormous strain. Already the fact that all the radii have to be first formed and afterwards reformed in the exactly opposite direction illustrates the severity of such operation. Naturally, the process gives rise to a lot of strain-hardening as well.

The forcible flow of metal generates enough heat to render handling of finished shells by hand impossible; up to 650°F can be expected in some situations. The steaming-hot shells can fracture on impact, or collapse from a sudden gust of cold air, which makes their ejection difficult. Where ironing without adequate vents is attempted, the trapped hot air may distort the shell by bulging its sides. The high temperature transfers to the die components too, enforcing changes of their sizes and changes in their fits. Perhaps water-cooled blocks, similar to those used for injection-molding blocks, which are riddled with cooling channels, should be designed to dissipate some heat.

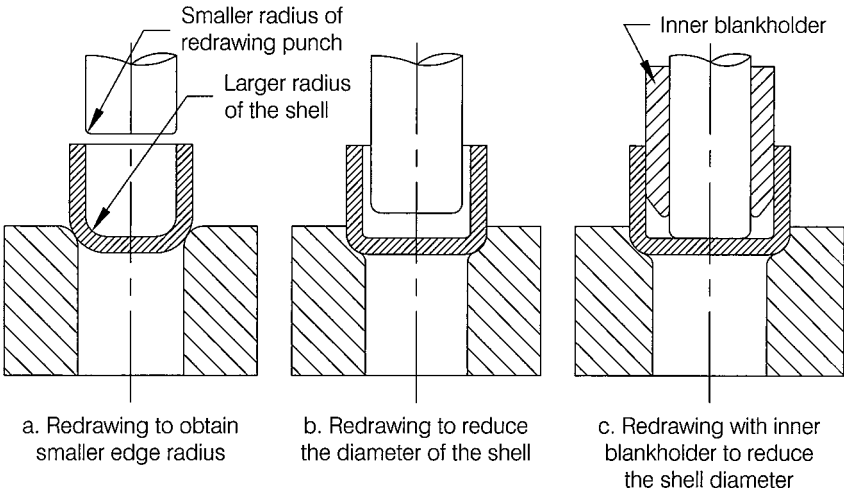
Smaller radius of redrawing punch
Larger radius of the shell
Inner blankholder
a. Redrawing to obtain smaller edge radius
b. Redrawing to reduce the diameter of the shell
c. Redrawing with inner blankholder to reduce the shell diameter

FIGURE 9-67 Redrawing operations.

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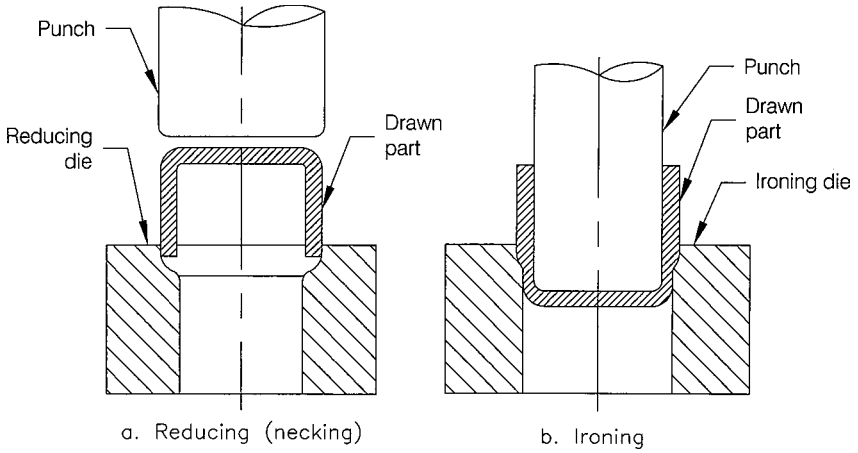

FIGURE 9-68 Reducing and ironing.

The selection of proper lubricants for this process is hampered too, since not many can withstand such high temperatures. Often, soap was found to be the lubricant of choice with such severe drawing operations.

Jerry Arnold recommends to reverse-draw in a press equipped with double acting ram, with independent pressure controls for each ram.* The speed of the press should be constant and slow, in the vicinity of 40 in. [1000 mm] per minute. The press tonnage must be constant as well, and of such a magnitude, as to allow for reversal of the bottom of the shell. Titanium carbide surface treatment for high friction areas of the die may be found useful.

However, recommended die radii with respect to the stock thickness cannot be honored, as their value would rather be dictated by the difference between drawing diameters d_1 and d_2 (see Fig. 9-70). Figure 9-71 shows drawing of a half-round shape.

Reverse drawing is advantageous for thinner materials, where $2t/d_1 = 0.2$ and for larger ratios of the diameters' difference, $d_1/d_2 = 1.4$.

With thicker materials, $2t/d_1 = 0.1$, this type of redrawing is not recommended.

The drawing method shown in Fig. 9-72 combines the regular drawing process with that of reverse drawing in a single stroke of the press. The drawing punch shaped as a ring, draws the material down, where it is redrawn by an ascending bottom punch. Spring-loaded drawing cushions are added for prevention of wrinkles and for stripping of the part off the bottom stake/punch.

9-8-2 Drawing of Spherical Shapes

Drawing of objects with spherical bottoms is more difficult than drawing of cylindrical shells. First of all, considerable deformation is generated in the curved portion, and the prevention of wrinkling is also impaired. Second, parts like these tend to spring back, especially if drawn in solid tooling.

*The book *Practical Aids for Experienced Die Engineer, Die Designer, and Die Maker*, by Jerry Arnold.

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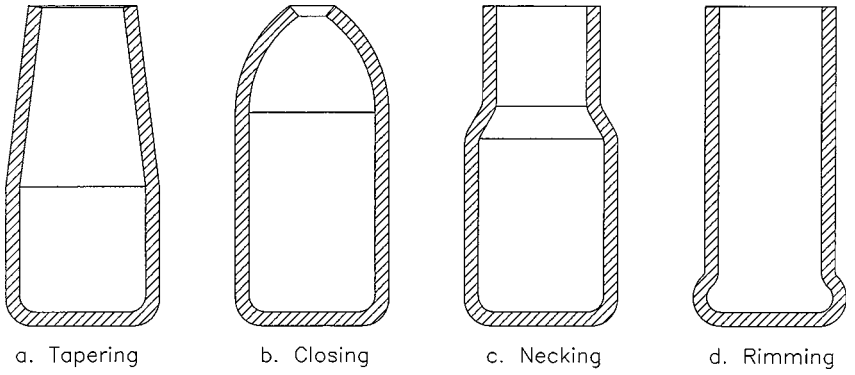

FIGURE 9-69 Reducing samples.

There are quite intensive deformation processes within that portion of drawn material which is in contact with the punch. At the beginning of the drawing sequence, the punch presses against a large unsupported area of blank, which is free to become wrinkled anytime. At the point of contact *A*, in Fig. 9-73*a*, there is an equally distributed radial and tangential tension. But at the point of contact *B*, which can be found at the beginning of the die radius, only a radial tension may be found, along with a tangential compressive stress. Stretching of the material causes thinning of the wall and often may result in breakage.

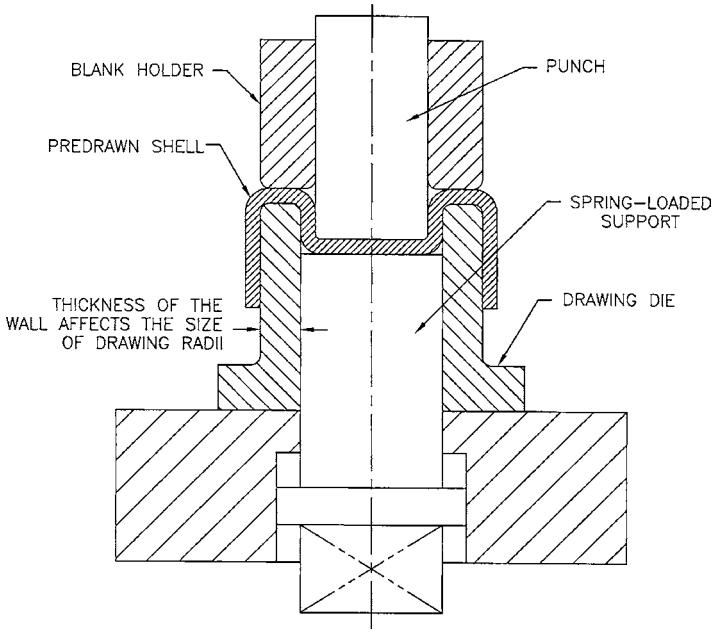

FIGURE 9-70 Reverse drawing.

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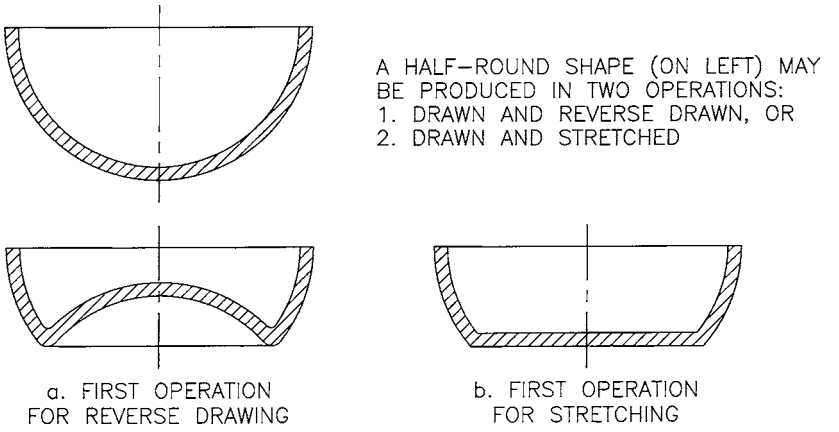
A HALF–ROUND SHAPE (ON LEFT) MAY
BE PRODUCED IN TWO OPERATIONS:
1. DRAWN AND REVERSE DRAWN, OR
2. DRAWN AND STRETCHED
a. FIRST OPERATION
FOR REVERSE DRAWING
b. FIRST OPERATION
FOR STRETCHING

FIGURE 9-71 Drawing of a half-round shape.

In cases where the spherical radius of the bottom $R_{\text{sphere}} > d/2$ and the height of the cylinder is quite small, the stability of the part in areas not retained by the tooling is endangered. Wrinkling may occur, and it may be eliminated only where the following relationship exists:

$$\frac{100R_{\text{sphere}}}{t_0} \geq 1.3$$

Some control over the drawing process may be achieved with either reverse drawing or through the inclusion of draw beads.

The number of needed drawing passes to produce a spherical-bottom cylindrical shell may be assessed the same way as with regular cylindrical shells, provided the condition $R_{\text{sphere}} < d/2$ applies, where $M = d/D_0 = 0.71$ max, or $K = D_0/d = 1.4$ max.

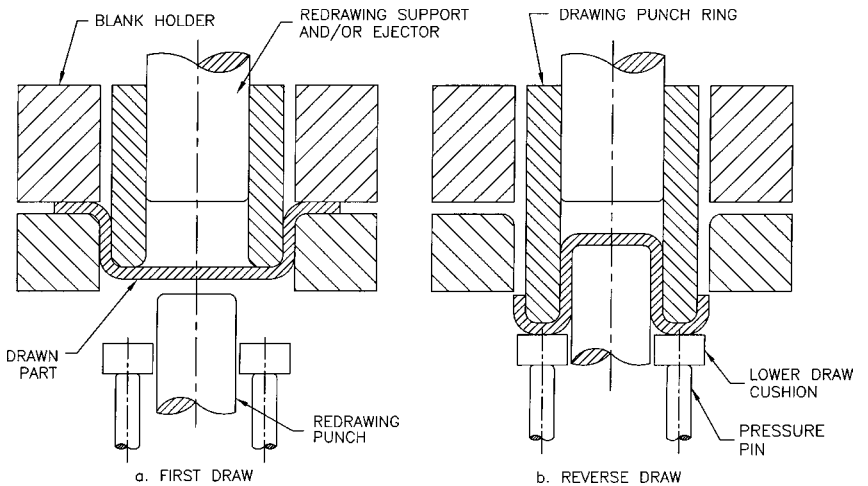

FIGURE 9-72 Reverse drawing combined with regular drawing.

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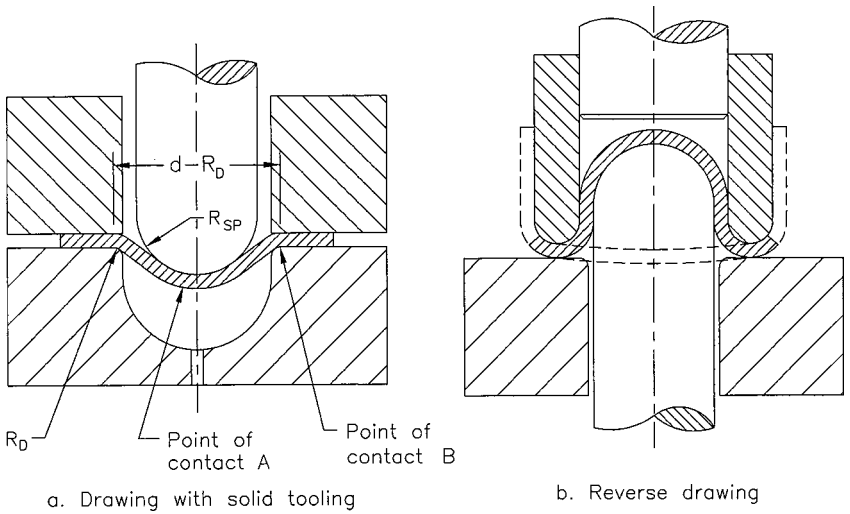

FIGURE 9-73 Drawing of spherical shapes. Reprinted with permission from Zdeněk Macháček and Karel Novotný, *Speciální Technologie I.*, published by ČVUT, Brno, Czech Republic.

The coefficient of severity of draw M is constant and for that reason may not be reliable as a guideline in evaluation of the amount of needed drawing passes. Rather a percentage of blank thickness to blank diameter should be used. Where a single drawing pass is contemplated, as followed by a finishing draw, and a conditions below (left) apply, the corresponding recommended drawing practices (right) should be observed.

$\frac{100t_0}{D_0} > 0.5$ Either reverse drawing or regular drawing with a blankholder should be used.

$\frac{100t_0}{D_0} < 0.5$ Either reverse drawing or regular drawing with draw beads should be used.

$\frac{100t_0}{D_0} > 3.0$ Single-operation drawing with bottoming should be used. No blankholder is necessary.

9-9 TYPES OF DRAWING DIES AND THEIR CONSTRUCTION

Most often, drawn parts are cylindrical, with some marginal squares or rectangular shapes to be found. The drawing process, with dependence on its speed, the necessity of a blankholder, and the type of shell disposal, may be performed in either a single-action or a double-action die. Single-action dies are used for parts of greater material thickness (Fig. 9-74*a*). In double-action drawing, the blankholder is employed for the retention of the blank and it is attached to the second ram of the press (Fig. 9-74*b*).

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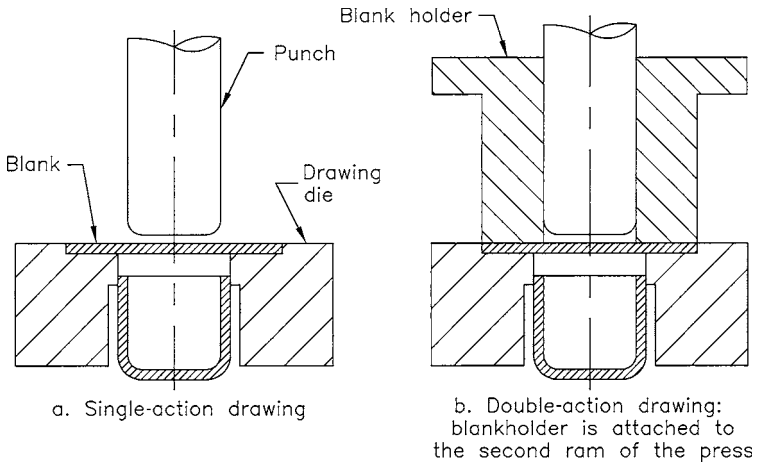

FIGURE 9-74 Two types of cup forming.

9-9-1 Double-Action Dies

Double-action dies are two in kind: Those that push the finished shell down through the opening in the die and those that bottom at the end of the drawing operation (Fig. 9-75).

Thinner stock should be drawn in double-action dies, for it should be restricted from movement by the blankholder's pressure; otherwise it will wrinkle. Wrinkled parts, no matter how many times redrawn, remain wrinkled, and therefore defective. This is attributable

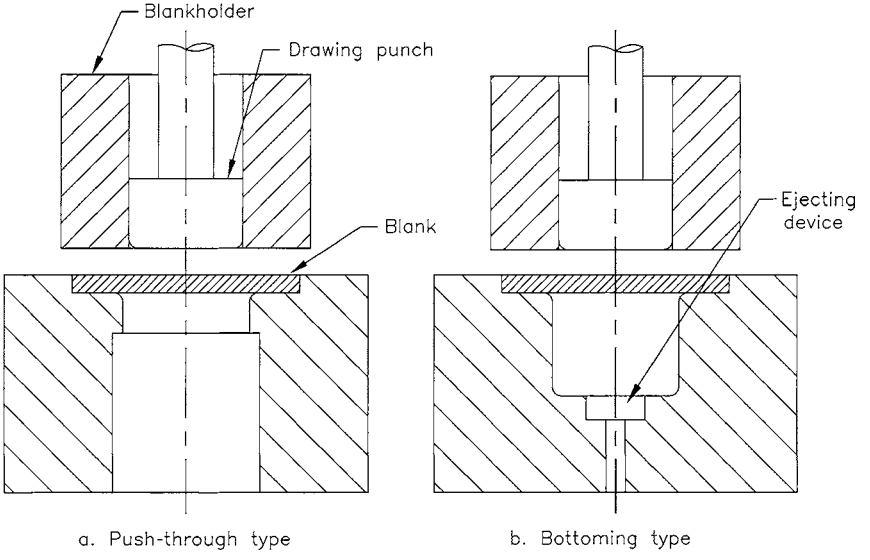

FIGURE 9-75 Double-action drawing dies.

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to the material's elastic limit, which must be exceeded for the part to accept a new shape. With redrawing for removal of wrinkles, all the force is applied in the direction in which they were formed, which does not provide for surpassing of the material's elastic limit. This can be accomplished only by applying the pressure from the opposite direction of that in which wrinkles were formed.

The blankholder's pressure in double-action drawing is adjustable, so that it clamps the blank firmly, regardless of possible thickness deviation. It secures the metal from any movement, prohibiting it from following the drawing punch too rapidly, and getting congested in the die.

9-9-2 Triple-Action Dies

Triple-action dies are used where additional die work is to be performed simultaneously with the basic drawing. Such dies may be used for blanking-embossing-drawing, or blanking-drawing-compressing, or blanking-drawing-drawing and similar arrangements (Fig. 9-76).

Triple-action dies are often used in replacement of bottoming double-action dies (see Fig. 9-75*b*), where the finished part has to be pushed up. In triple-action tooling the finished shell may still be disposed off through the bottom opening in the die, which often may be preferable.

9-9-3 Drawing With Flexible Tooling

Drawing with flexible tooling (such as rubber and fluids) often allows for deeper draws and greater reduction ratios than hard, inflexible punches and dies. The radius of the flexible die R_D as seen in Fig. 9-77 is capable of altering its shape under the pressure of fluid P_{FL}. Such a shape may take the form of either higher or lower line, depending on the amount of pressure P_{FL} which may be adjusted during the drawing process.

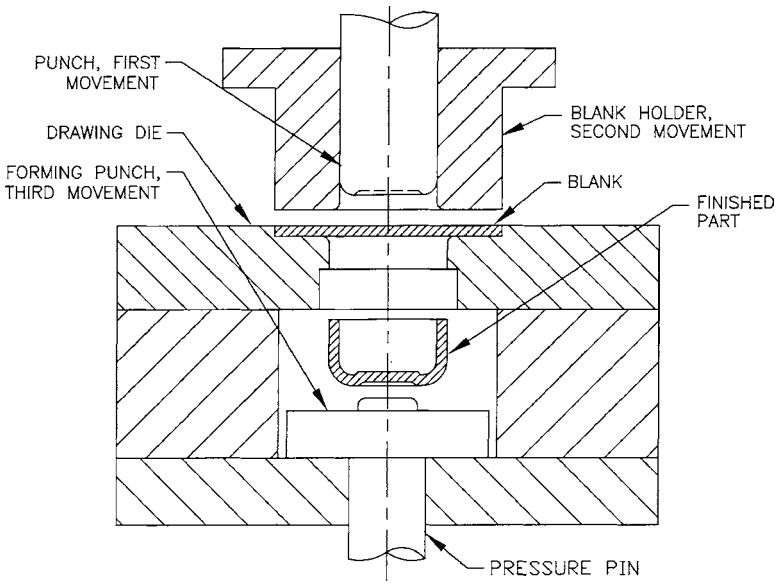

FIGURE 9-76 Triple-action die.

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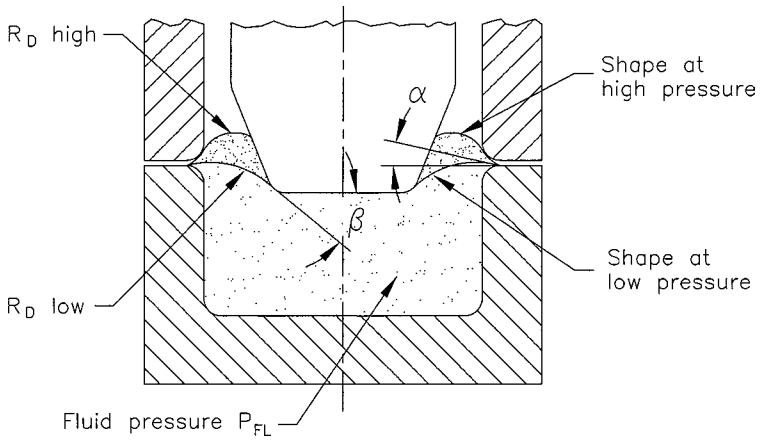

FIGURE 9-77 Shape of the flexible drawing die and its variation with the pressure.

The required fluid pressure P_{FL} may be calculated by using a formula

$$P_{FL} = \frac{2tS(R_P \cos\alpha + R_D \cos\beta)}{R_P^2 - R_D^2} \tag{9-33}$$

where t = material thickness
S = tensile strength of drawn material
R_P, R_D = instantaneous radii of the punch and die
α = angle of tangent at the point of transition of the wave into the flange
β = angle of tangent at the point of transition of the wave into the vertical height of the shell

The result comes out in lb/in.^{2} or in tons/in.^{2} according to the tensile strength's denomination.

The radius of the curve of the die R_D may be obtained:

$$R_D = \frac{R_P}{\cos\alpha + \cos\beta} - t \tag{9-34}$$

The radius of the die R_D has a considerable influence on the stability of the drawing edge, which in this case is adversely affected by the flexibility of the die surface.

Because of possible regulation of the pressure of fluid even during the drawing operation, flexible drawing tooling is unsurpassed by any other manufacturing method. It may be utilized for drawing of simple shapes, as well as for complex ones, such as spherical, conical, or hyperbolic cross sections, which will otherwise be prone to the formation of wrinkles.

Drawing with flexible tools may be divided into two sections, where the first utilizes the *Marform* or *hydroform processes* of drawing. In the *Marform process* (Fig. 9-78), the rubber insert serves as a blankholder, retaining the blank on the surface of the stationary punch. The *hydroform process* (Fig. 9-79) draws the part with the pressurized fluid. The *hydrodynamic forming process* and the *hydromechanical drawing process* are shown in Figs. 9-80 and 9-81.

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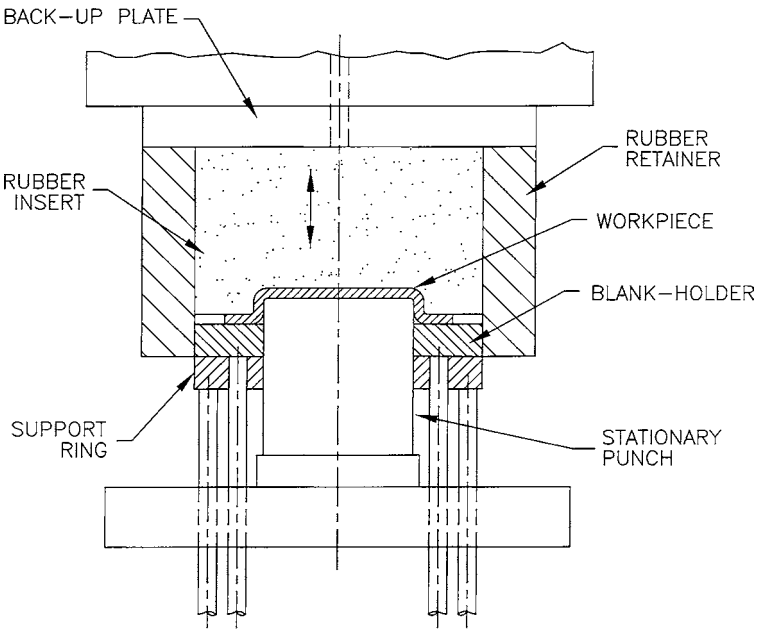

FIGURE 9-78 Marform drawing process.

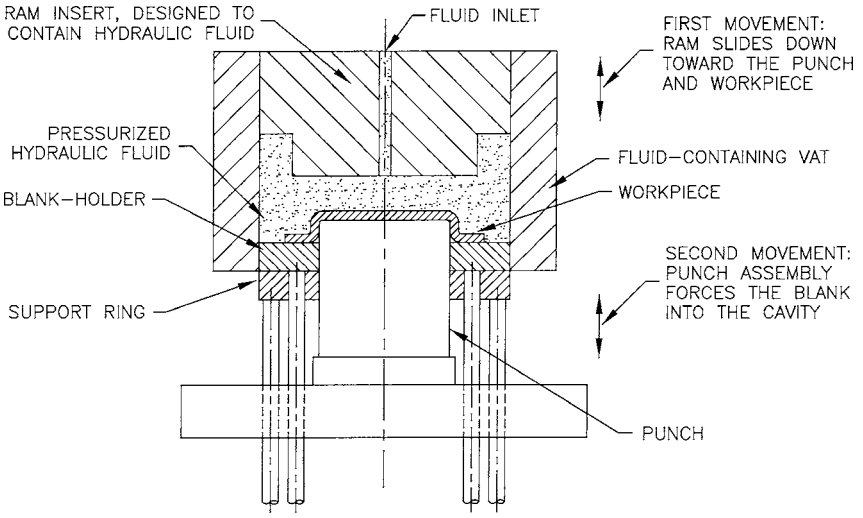

FIGURE 9-79 Hydroform drawing process.

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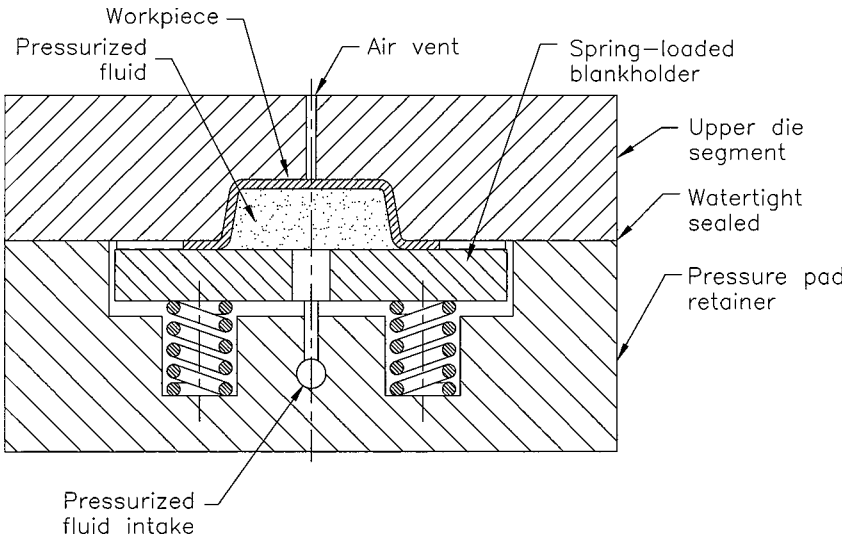

FIGURE 9-80 Hydrodynamic drawing process.

The second group of drawing techniques using flexible tooling utilizes the *Verson-Wheelon* or *Asea Quintus* process (Fig. 9-82), where a flexible rubber sack exerts its pressure on the part. The drawn object is wrapped around the punch, often without any assistance of a blankholder, which sometimes causes waves and wrinkles in the material.

The first group of drawing techniques regulates the pressure of the flexible element P_{FL} by the counterpressure of the blankholder. Such a counterpressure is governed either by a regulating valve or by a microprocessor. It allows for a decreased drawing pressure at the beginning of the drawing operation, with subsequent adjustment to higher levels when the drawing process demands it.

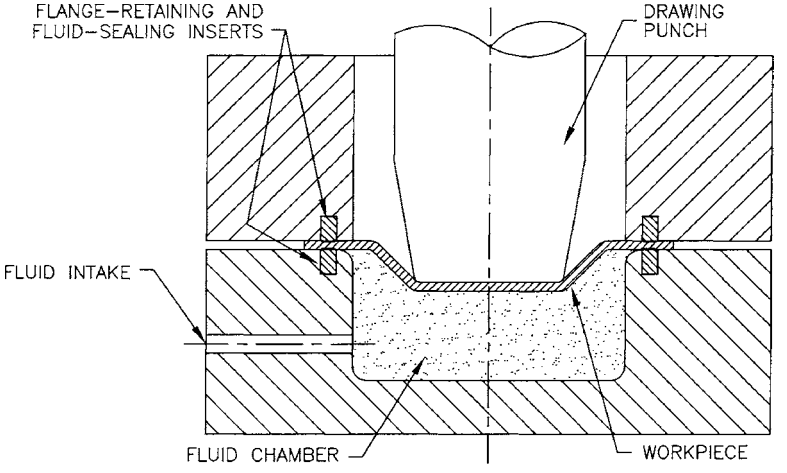

FIGURE 9-81 Hydromechanical drawing process (with workpiece retention).

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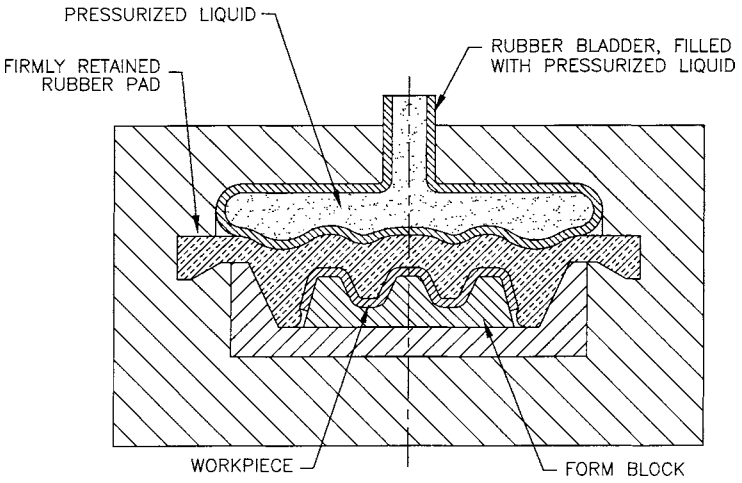

FIGURE 9-82 Verson-Wheelon drawing process.

The second group suffers from the material's tendency to wrinkle. This is due to the lowered amount of radial tension (a tension denominated by the actual amount of deformation), which leaves a space for the rise of tangential tension.

9-10 BLANKHOLDERS AND DRAW BEADS

blankholders also called *binders* are employed to retain blanks under the punch. Their pressure on the material secures it from being recklessly pulled into the die and ruined there, while controlling the amount of metal redistribution from the flange into the height of a shell. With inadequate pressure of the blankholder, the material may not be sufficiently retained, which will result in its greater than planned volume flowing into the body of the shell. Often such action will introduce the formation of wrinkles on the surface of the flange or collapsing of the flange and other defects.

As the metal passes over the edge of a die, its flow is no longer controlled by the pressure of a blankholder and it is free to form wrinkles within the body of a shell.

To avoid the formation of wrinkles or buckling, chamfered dies are found useful. However, when drawing a stock thinner than 0.062 in. [1.6 mm], radiused corners should be used instead. Experiments have proved that buckling does not occur where the ratio of the flange width to metal thickness is less than 3 to 4.

According to their construction, there are several types of blankholders, as shown in Figs. 9-83 and 9-84.

blankholders, shown in Fig. 9-83*a* and *b*, are of simple, basic construction, permitting an adjustment of their pressure. For this advantage, they are preferred throughout the industry, especially where a thin stock, which is always prone to wrinkling, is drawn.

A blankholder (Fig. 9-84*a*) is used where thickening of the flange during the drawing process is required. The height of the nest is crucial to the proper outcome, as with too large a gap, wrinkles are obtained. The proper space between the flange and the bottom of the blankholder should be 25 to 50 percent smaller than the difference in thickness between the flange before drawing and its anticipated thickness at the end of drawing.

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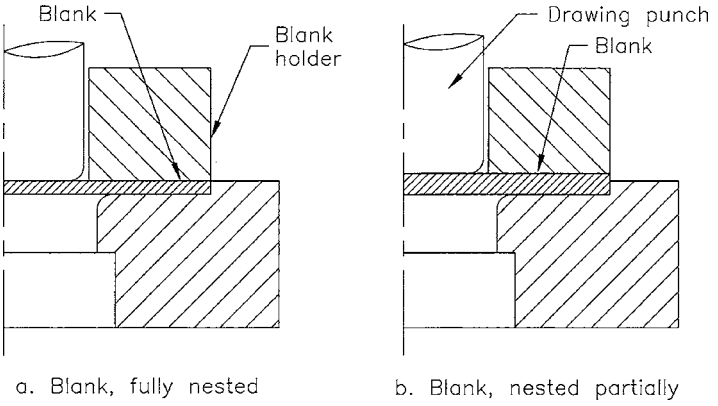

FIGURE 9-83 Adjustable-pressure blankholders.

The height of the thickened flange may be obtained from the equation

$$\frac{t_1}{t} = \sqrt{\frac{D}{D_1}} \tag{9-35}$$

where t_1 = thickness of drawn part's flange
t = thickness of the blank
D = diameter of blank
D_1 = diameter of flange, or mean diameter of shell without flange

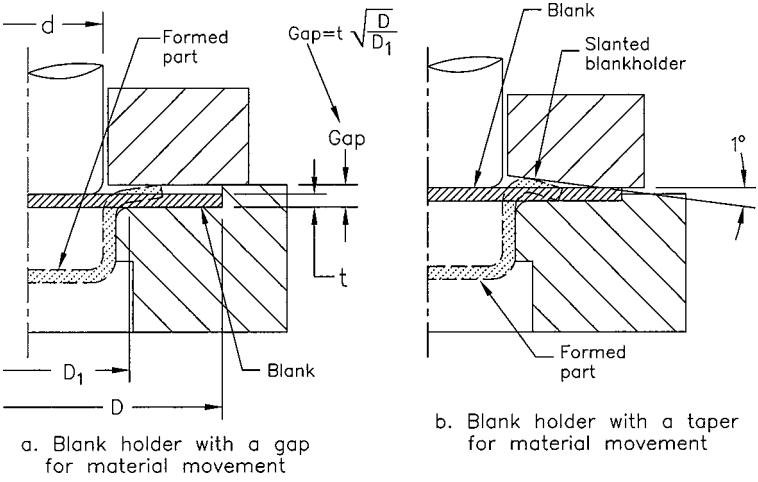

FIGURE 9-84 blankholders.

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The height of the nest may be assessed as

$$t_{\text{die}} = t\sqrt{\frac{D}{D_1}} \tag{9-36}$$

The blankholder shown in Fig. 9-84*b* is an alternative of the blankholder in Fig. 9-84*a*. Its pressure is confined within the circumferential area of the flange, which allows for gradual thickening of its profile. The angular inclination may be around 1°, as it is not overly critical. This type of blankholder is said to decrease the necessary drawing force.

9-10-1 Drawing Without a Blankholder

Some drawing operations can be performed without blankholders. Evaluation of such a possibility can be done on the basis of several methods of assessment. Some theories consider a thick stock eligible for drawing without a blankholder; others judge the possibility of eliminating the blankholder by altering the geometry of the drawing die.

According to some other opinions, shells may be drawn without a blankholder if the opening in the die is five to six times the metal thickness per diameter smaller than the blank. The exact amount of this difference in a given case is based on the rate of reduction during the drawing stage. It may be expressed mathematically as a percentage of reduction *R* percent:

$$R\% = \frac{100t(5 \text{ to } 6)}{D} \tag{9-37}$$

Requirements regarding the geometry of the position of a blank with regard to the drawing edge are shown in Fig. 9-85. These arrangements allow for drawing of a shell without using a blankholder.

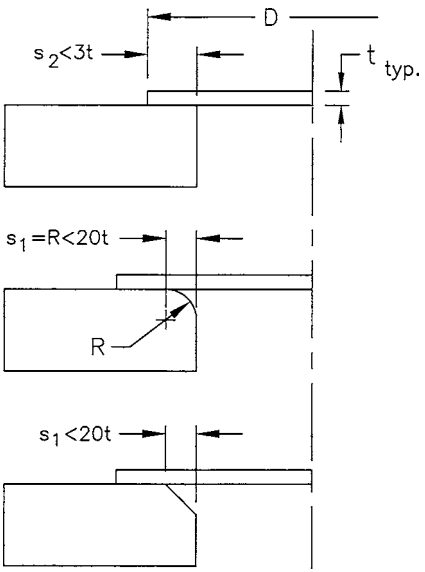

FIGURE 9-85 Dimensional requirements for drawing shells without blankholders.

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For eligibility to draw without the blankholder, the radius or chamfer R of the drawing die must be smaller than $20t$, as shown in Fig. 9-85.

According to Freidling's theory, evaluation of the possibility of drawing without a blankholder depends on the percentage value of the ratio of stock thickness to the diameter of the blank. The formula to use for such an evaluation is described in Sec. 9-4-3, Eq. (9-27).

CSN 22 7301 evaluates the need of a blankholder by the formula

$$A = 50\left(z - \frac{\sqrt{t_0}}{\sqrt[3]{D_0}}\right) \tag{9-38}$$

where z = constant, related to the drawn material as follows:

for deep-drawing steel strip, $z = 1.9$
for brass strip, $z = 1.95$
for aluminum and zinc strip, $z = 2.0$

$A \geq \dfrac{100d}{D_0}$ blank holder is necessary

$A < \dfrac{100d}{D_0}$ blank holder is not necessary

Deep-drawing materials thinner than 0.020 in. [0.50 mm] must always be drawn with a blankholder.

9-10-2 Blankholder in Conjunction with Draw Beads

The lifting force of draw beads against the blankholder is enhanced by the flow of material along their profile. This occurrence may further be increased by an inappropriate geometry of the bead or by the inclination of its walls, as well as by the addition of successive beads. In order to promote the correct functionability of draw beads (Fig. 9-86), which in

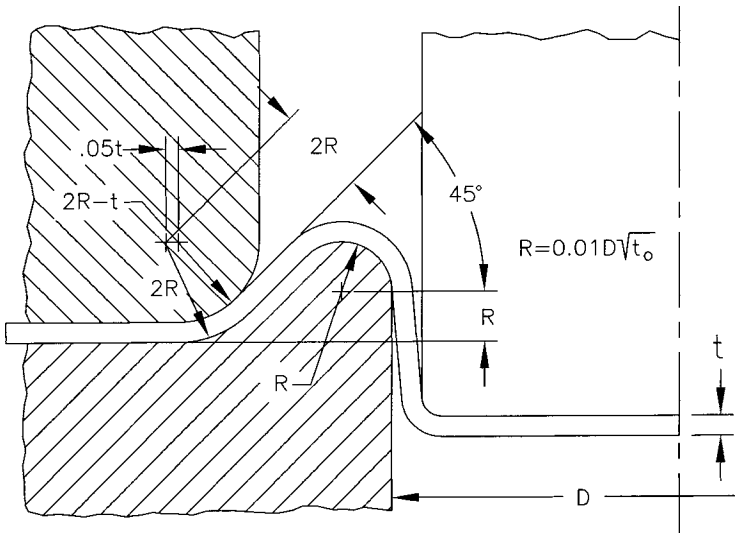

FIGURE 9-86 Draw bead design.

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return means a proper resistance to the flow of material, the blankholder's pressure should be as close to its lower limits as possible.

However, with lowering of the pressure of the blankholder, and if in case the bead design has any imperfections, the lifting force of the flange material sliding past may totally disqualify its function. Therefore, the lower limits of the blankholder's pressure, in ideal conditions, should be the same as forces of the sheet-metal flange, which is causing its lifting.

Calculation of such pressure should consider that deformation of the part's flange does not alter its thickness. The yield stress should be taken for uniform. Such a calculation should further neglect any frictional resistance along the beads' shape, considering the bead too small in comparison with its diametral value and that of the flange.

The need for a blankholder's pressure is considerably increased where the walls of a bead are made steeper or by an addition of supplementary bead lines. These conditions also decrease the blankholder's sensitivity, which is the ratio of the drawing resistance of the flange to the increase in blank-holding load.

Draw beads on the die surface, with corresponding shapes on the blankholder, affect the material tension, reaching up to the wall of drawn parts, and have a considerable influence on the amount of blank-holding pressure, which is decreased in this case.

9-10-3 Blank-Holding Pressure

The pressure exerted by the blankholder on the flange was found to be somewhere between 0.005 and 0.067 percent of S_Σ, where S_Σ is the sum of yield strength and tensile strength of the drawn material. The blank-holding pressure was found to vary, even though very slightly, along with the variation of metal thickness.

To prevent wrinkling, the pressure needed for various materials is approximately as shown in Table 9-17.

The blankholder's pressure may be adjusted either by application of springs or by means of hydraulic or pneumatic devices. As far as the spring-loaded support is concerned, urethane pressure pads, strippers, and shedders were found to provide greater pressure per unit area than wound springs.

The numerical value of the blankholder pressure is important mostly for calculations of the total drawing pressure. To actually fine-adjust the blankholder pressure for the given value may have been difficult previously. Today, with the aid of computerized press controls, load cells for monitoring of the pressure and PLC's for implementation of the measured data, and adjustment of the press and die components' function, fine-tuning of

TABLE 9-17 Pressure of Blankholder with Respect for the Material Drawn

Material	Pressure	
	lb/in.^{2}	MPa
Deep-drawing steel	300–450	2.0–3.0
Low-carbon steel	500	3.5
Aluminum and aluminum alloys	120–200	0.85–1.40
Aluminum alloys, special	500	3.5
Stainless steel, general	300–750	2.0–5.0
Stainless steel, austenitic	1000	7.0
Copper	175–250	1.25–1.75
Brass	200–300	1.40–2.0

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blankholder's pressure is a perfectly feasible process. In production, the blankholder pressure is adjusted with respect to the part drawn. The object is additionally observed for appearance of wrinkles, buckling, or tearing, with the pressure corrected accordingly.

Aside from drawn-material mechanical properties, blankholder's pressure is additionally affected by the type and length of draw beads or draw steps, plus the size of the drawing punch.

9-10-4 Draw Beads and Their Design

Draw beads are structural addition to the flat die surface, which are intended to slow the drawn material's progress down the die cavity. With dependence on their height and on their radius, the drawn material can be slowed down only very slightly, or it can be almost totally stopped.

Draw beads can be machined along with the drawing die surface, or they can be inserted into a recess, or welded where appropriate. Obviously, their shape must blend with the die surface without any interruptions or abrupt transitions, for any such defects will transfer to the part in the form of scars, tears, or other distortions.

Material of draw beads must be highly resistant to abrasion, as the advancing drawn stock abuses their surface considerably. With greater height or sharper radius of the beads, more forming and reforming takes place, which results in greater slow-down of the material and also in greater strain hardening and greater heat. (See Fig. 9-87).

Step beads, shown in Fig. 9-88, do not produce as much strain hardening as conventional half-round draw beads. Here, the material is not so severely formed, unless of course, it does not become squeezed too tight by the binder. To avert such condition, standoffs are used to control the metal flow consistency.

A sample of standoffs is shown in Fig. 9-89. These are small metal blocks placed at approximately three places around the part's circumference. They are usually mounted between the draw die and the binder to keep the offset needed for the material thickness. The height of standoffs is usually 10 percent greater than the thickness of drawn material, and their ease of adjustment can provide for any variations needed. Their surface area should be as large as possible and they should be made of impact-resistant tool steel.

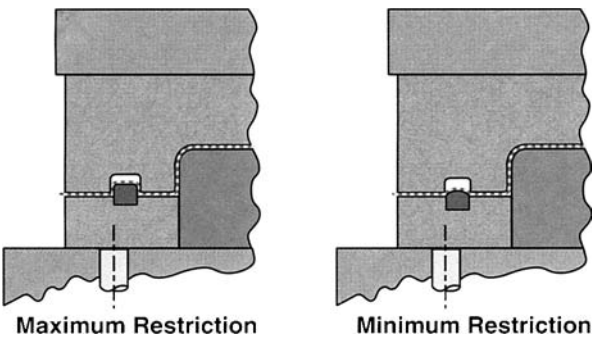

FIGURE 9-87 Draw beads and their function. The shape and size of a draw bead determine the amount of restraining force exerted on material. A sharp radius decreases material flow, while a large radius allows more material to flow. (*From: The STAMPING Journal®, March/April 2000, page 30, by Art Hedrick. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

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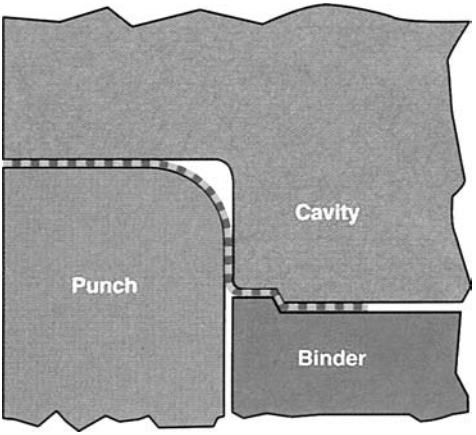

FIGURE 9-88 Step bead. A step bead typically causes less strain hardening in the material being formed because the metal is not forced to bend and unbend as much as it is by a draw bead. (*From: The STAMPING Journal®, March/April 2000, page 30, by Art Hedrick. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

Higher step beads are also called *lock beads*. These formations can totally stop the material from moving, in which case it will be stretched, not drawn, by the downward action of the punch.

Most probably the best calculation of draw beads' application can be achieved through the Internet access. At Autodie International, Inc., a group of researchers developed a whole library of case histories, with significant process parameters and their influence on various drawing operations. By accessing this database and navigating through various geometries, the best scenario can be found and adapted per existing requirements. A sample result of draw bead calculation is included in Fig. 9-90.

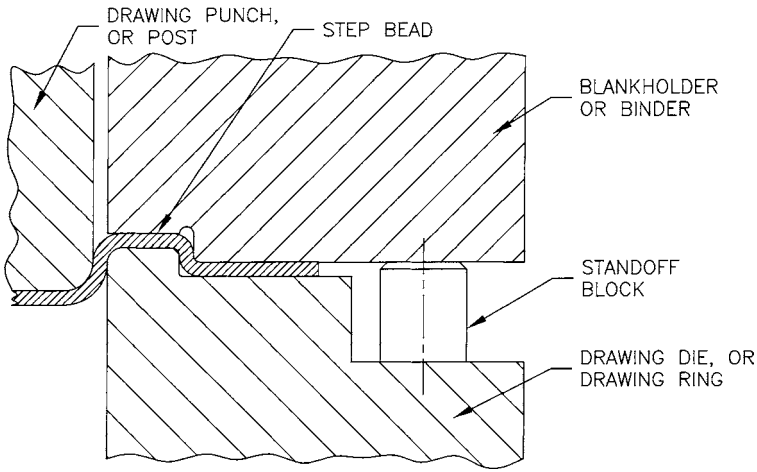

FIGURE 9-89 Standoff block in drawing.

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Draw Bead Calculator		
Calc. Mode: GEOMETRY	Bead: RECTANGULAR	Restrain Force: 15.250 kN
Groove Radius: 4.419 mm	Bead Radius: 4.419 mm	
Bead Clearance: 2.000 mm	Bead Depth: 10.000 mm	
Groove Width: 15.000 mm	Sheet Width: 100.000 mm	
Sheet Thickness: 1.000 mm	Friction Coefficient: 01.000 mm	
Strain Hardening Exponent (n): 0.200	Strain Rate Exponent (m): 0.001	
Normal Anisotropy (r): 1.500	Test Strain Rate: 0.007 mm/sec	
Strength Coefficient (K): 500.00 MPa	Elastic Modulus: 200000. MPa	
Yield Strength: 250.000 MPa	Punch Speed: 100.000 mm/sec	
<< Use ESC key to exit the table <<		

FIGURE 9-90 Example of draw bead calculator screen information. (*From: MetalForming Magazine®, February 1999, page 50, Stamping Research, MF. Reprinted with permission from PMA Services Inc., Independence, OH.*)

9-10-5 Heated Blankholder and Cooled Drawing Punch and Die

Already back in 1987, deep drawing with a cooled punch and die and heated blankholder (see Fig. 9-91) was considered a well-known process. Based on the Alder-Phillips research, this drawing application demonstrates a considerable increase in drawing ratio limits achievable in a single drawing pass.

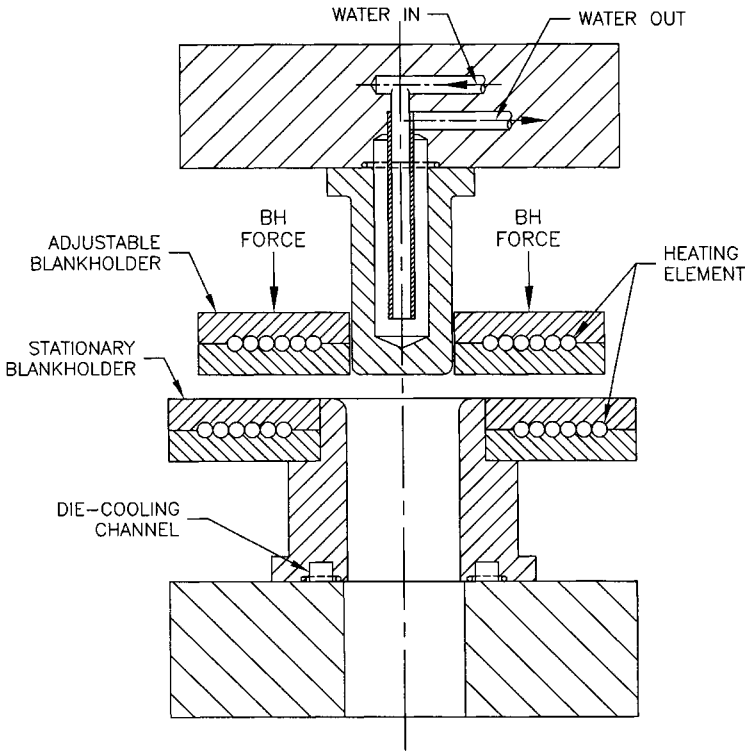

FIGURE 9-91 Drawing with a heated blankholder and a cooled punch and die.

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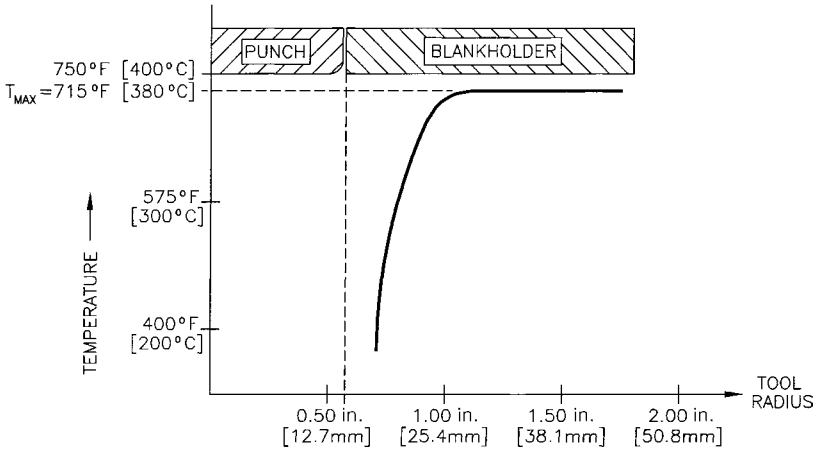

FIGURE 9-92 Heated blankholder temperature distribution.

The distribution of the blankholder's heat is shown in Fig. 9-92. At 715°F [380°C], the drawing ratio was found at its highest, yet decreasing afterward, with implementation of higher drawing speeds. The drawing speed used was in the range of 0.50 to 4.75 in./min. [12 to 120 mm/min.].

Deep drawing with a heated blankholder depends heavily on the properties of the material, especially on its modulus of elasticity and its forming qualities. Since heated drawing is carried out at approximately recrystalizing temperatures of the material, the strain rate becomes an important factor to deal with.

9-11 DEFECTS CAUSED BY DRAWING PROCESS

The drawing process places a considerable strain on the material, which sometimes responds by failing during the manufacturing process. Many such defects are mainly visual, such as wrinkles, but there are others, much more insidious, which affect the part's functionality.

9-11-1 Breakage of Shells

If tearing or breakage occurs in shells drawn from a thin stock, it may be caused by too small radii of the drawing punch or die. Shells also break around their bottom when the ratio of the blank diameter to the shell diameter is too great. Such a drawing process exceeds the strength of a material and a fracture will appear. As a rule, shells should not be drawn deeper (in a single pass) than the amount of their blank diameter. Drawn parts may also break because of various other reasons, such as

- Insufficient clearance between the punch and die
- Excessive pressure of the blankholder
- Excessive friction between the material and tooling

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Other aspects not to escape the investigation when looking for the source of shells' breakage, is the ductility of the material with regard to its thickness. Sometimes, a continuous checking of all incoming stock's ductility may need to be performed, if problems along these lines were spotted.

Where the punch and die are not concentric, tearing of shells within the same area will occur, no matter what precautions are taken. The tooling, especially punch, die, and blankholder, must also be checked for flatness and surface finish. A step in the tooling surface will definitely bring about problems in drawing process.

Occasionally, breaks can occur where rolled seams in the sheet metal are present. These seams, almost invisible to the naked eye, will propagate under the strain of drawing forces, cracking along their lines.

9-11-2 Intergranular Cracking

Intergranular cracking makes its presence known by the emergence of long, vertical cracks, reaching from the top of a shell, down to the bottom. These cracks, caused by the residual tensile stresses within the material, may be completely invisible and yet the part may be prone to cracking perhaps later on, already in service.

To test a drawn cup for the existence of intergranular cracking tendency, a corrosive liquid can be used. Remaining in the cup for a certain period of time, the corrosive liquid will eat through the cracks and these will open up like a flower. The pattern thus created will be quite similar to that, shown at the beginning of this chapter, in Fig. 9-2.

Where the cups were stress relieved for removal of residual stresses right after forming, no cracks will be present.

Intergranular cracking is caused by the displacement of material during the drawing process. Where a drawn, diametrally restricted part is ejected from the die, the springback of the material has a tendency to force its structure back, toward its basic shape, in this case to a round blank. By doing so, the diameter of the cup bulges, giving rise to residual tensile stresses at the same time.

With box-type drawn objects, the cracking is called *compression cracking*, since it occurs at the corners, where the material is in compression. The shape and location of these cracks resembles those of a round shell, which is logical, considering the fact the rounded corners of the box do resemble a quarter of the shell, each.

Compression cracking is insidious in that, the part may look absolutely perfect and on impact, or perhaps with time the cracks develop and propagate. As with round shells, stress relieving after forming removes the residual stresses from the material and along with them, it removes the material's tendency to cracking.

9-11-3 Alligator's Skin

"Alligator's skin" may be observed on deep-drawn shells which are made from a material with a hardened surface. This defect appears where the movement of drawn metal is considerable, forcing the inner, annealed layers to flow along more readily and into greater depths than the upper crust, which is hardened. The latter, when stretched beyond its elastic endurance, tends to pull apart and crack.

Hardening of the strip-steel surface may be caused by strain hardening of the material during the rolling process. In order to diminish brittleness of the rolled material, the cold-rolled strip is annealed prior to its arrival at the last rolling pass. This last stage of its production is used to bring the material thickness to the correct size. However, should the reduction in thickness be excessive, strain hardening of the upper layer will result.

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9-11-4 Grain Growth

Grain growth is a rather peculiar condition of material that has been cold worked and annealed afterward. It consists of a considerable enlargement of the material grain, which almost explodes in size. The sign of this occurrence is the roughening of the surface, either in spots or in the whole strip or sheet.

Grain growth occurs most often in cold-rolled, low-carbon steels, below 0.2 percent of carbon, and in some aluminum alloys. The annealing process, when performed at 1250 to 1650°F [680 to 900°C], causes the grain to grow in size, even though the intensity of such growth is closely related to the amount of cold work the material was exposed to previously. Grain growth appears in critically strained areas and impairs the plastic flow of the material, making it highly irregular.

Products affected by grain growth will fail in service when exposed to comparatively minor operational parameters. In deep-drawn shells, grain growth appears at their bottoms, the area most affected by cold working.

One method of preventing the grain growth within the material is to choose lower annealing temperatures, which should not bring the material into its recrystallization stage. With steels of a higher carbon content, higher annealing or normalizing temperatures, reaching beyond the critical temperatures of 1450 to 1750°F [790 to 950°C], may alleviate the problem.

9-11-5 Galling

Galling is a result of localized adhesion of the part to its tooling. It is related to the plastic deformation caused by ironing of areas with rough surface finish. The occurrence of galling is considered as caused partially by the breakdown of lubricant, which may have been wiped off during the drawing process, and exposed the drawn material to contact with its tooling. Such sudden contact produces scars on the part, called galling.

A majority of galling occurs in parts where draw beads have been used in the process. Perhaps the increased pressure of draw beads on the material causes the breakdown of a lubricant, and subsequent damage to the part. The smooth surface of a die, turning into a large bearing section, may expose the material to galling.

Galling is suspected to greatly impair the drawing capacities of recently designed low- and high-yield-strength steels, such as low-alloy steels containing columbium and titanium, in their decarburized condition. Experimental testings of these alloys found the formation of debris that caused the galling to occur.

Where galling occurs in a drawing process, it is always preceded by the presence of loose metal particles, deposited on the drawing tool and even contained within the lubricant. Some of these particles remain attached to the tooling, creating a buildup of material, especially in the vicinity of high-stressed zones, such as the die radius, blankholder functional surfaces, the area of beads, and the like. The final stage occurs when these obstacles, already too bulky, tear off the surfaces they have been adhering to and, placing themselves in the path of the drawn material, produce deep scratches or outright breakage of its surface.

The inclusion of lubricant containing high-pressure additives was previously considered a remedial treatment for galling. Such a solution in itself gave rise to wrinkling of the drawn shell or to the formation of waves within the shell. It made the parts stick to their tooling, caused difficulties in the cleaning process, and so on.

However, not much attention was ever given to the fact that galling is mainly caused by the roughness of the surface of the sheet, which, when consisting of too many gaps and other irregularities, promotes the occurrence of galling in the drawing process. Experiments

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(by Japanese researchers, Takahashi, Okada, and Yoshida) have proved that the roughness of the surface is directly proportional to the occurrence of galling.

During the drawing process, various small debris may get entrapped within the rough surface's valleys and gaps, creating minute obstacles around which more debris may accumulate as the process progresses. The highest of irregularities are then subjected to reduction in height, with the removed material being added to the mass already entrapped within the surficial roughness. Such leveling is called "rasp action" by mechanics.

Frictional forces between the drawn material and its tooling, especially during the repeated movements along the same surface, act further upon its already distorted structure. If the valleys in the material are not deep enough to contain all the material sheared by the movement, which in time will always happen, a growth of the deposited material will result, with subsequent tearing and damaging of the drawn product or even its tooling.

9-12 FRICTION AND DRAWING LUBRICANTS

Lubricants for a drawing process must have an adequate film strength in order to withstand the high pressures and high temperatures associated with drawing. The lubricant's wetting ability should be considerable as well, to spread readily over the ever-expanding surface area of the part. Oiliness control is of essence, since a certain amount of it is necessary, while its excess may prove harmful.

Drawing lubricants, as any other lubricants, must be nonaggressive toward the part, toward the tooling, the machinery, and the operator. Their application and removal must be uncomplicated and economical.

There is a variation in a lubricant's qualities with each material drawn. For example, aluminum alloys are more plastic and may be drawn into greater depths without tearing or fracturing. However, they also possess a high coefficient of friction, which, on the die side, must be decreased with proper lubrication. Such a decrease should be controlled, as an excessive oiliness of the lubricant will certainly produce slippage of the material, with resulting damage to the part and perhaps even to the die.

When selecting the lubricant for a given drawing operation, all subsequent manufacturing processes must be taken into account, such as heat treatment and surface treatment. Some lubricants, usually those of high lubricating qualities, are highly adherent and for that reason difficult to remove off the part.

9-13 DRAWING TONNAGE AND OTHER CALCULATIONS

A quick evaluation method, assessing the maximum drawing tonnage based on the thickness of material, shell diameter, ultimate tensile strength of the drawn stock, is as follows:

$$P_{\text{draw}} = 0.00157tdS \tag{9-39}$$

where S = tensile strength of the material

However, a more complex formula used for the assessment of the drawing pressure P_{DR} is

$$P_{DR} = AS_y\eta_c \ln E_c \tag{9-40}$$

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where A = area of cross section of a shell, $A = \pi dt$
S_y = yield strength of the material
η_c = deformation efficiency of drawing process (see Fig. 9-93)
E_c = cupping strain factor, in this case expressed in the form of its natural logarithm *ln*

Deformation efficiency factor η_c is a friction-related component, depending on the amount of strain factor. The product ($\eta_c \ln E_c$) from Eq. (9-40) may be replaced by an expression $[D/d - C]$, where C is a constant, ranging from 0.6 to 0.7. Equation (9-40) becomes

$$P_{DR} = AS_y\left(\frac{D}{d} - C\right) = -\pi dtS_y\left(\frac{D}{d} - C\right) \tag{9-41}$$

A total drawing force for dies using a blankholder consists of the combined drawing force and the pressure of the blankholder, or

$$P_{\Sigma-DR} = P_{DR} + P_{BH}$$

where P_{BH} is the pressure of the blankholder.

Another method of drawing force evaluation takes into account tensions within the drawn material. The formula to use is

$$P_{DR} = \pi t_0 S d_m \geq \pi t_0 \sigma_\Sigma d_m \tag{9-42}$$

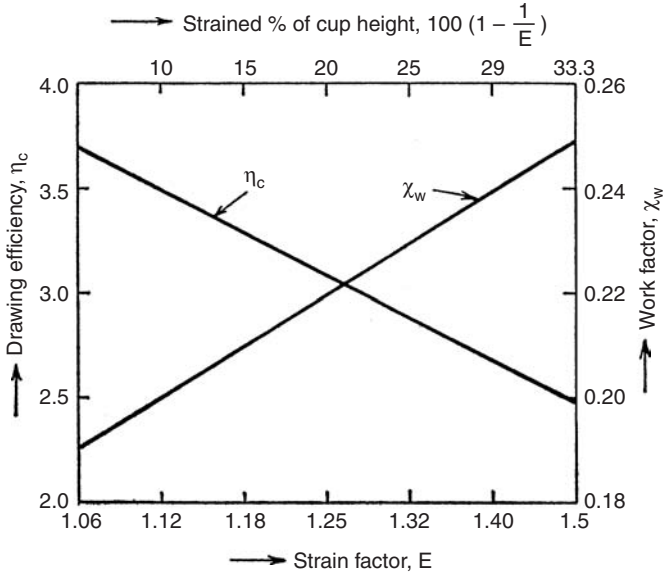

FIGURE 9-93 Relationship of the strain factor, work factor and drawing efficiency. (*From Frank W. Wilson, Die Design Handbook, New York, 1965. Reprinted with permission from The McGraw-Hill Companies.*)

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where d_m = mean diameter of shell
σ_Σ = total of all tension within the material, which may be calculated as follows:

$$\sigma_\Sigma = (\sigma_r + \sigma_f)(1+1.6\mu) + \sigma_b \tag{9-43}$$

where σ_r = radial tension
σ_f = tension caused by friction
σ_b = tension due to bending
μ = coefficient of friction

Ironing. In the ironing process, the vital information is the percentage of reduction of the wall thickness. This may be assessed by calculating

$$R_{i\%} = \frac{100(t_0 - t_1)}{t_0} \tag{9-44}$$

The reduction percentage, however, does not evaluate the strain of the material E_i, which can be expressed as the ratio of thickness variation, or

$$E_i = \frac{t_0}{t_1} \tag{9-45}$$

The result should be equal to

2.0 (50 percent reduction) for a single ironing pass
2.5 (60 percent reduction) for ductile and annealed materials

Ironing strain factors are shown in Table 9-18.

With multiple ironing operations, the action of strain hardening may diminish the ratio of strain factor of the material in every ironing pass.

TABLE 9-18 Ironing Strain-Factor Values and Relative Ability of Ironing of Various Materials

$E_{it,\max}$	Relative ironing	Reduction R_i, %*	Material (example)
1.25	Extremely little	20.0	(For third draws)
1.4	Very little	28.6	
1.6	Little	37.5	(For second draws)
1.8	Medium	44.4	Steel
2.0	Medium-good	50.0	Stainless
2.24	Good	55.4	Copper
2.5	Very good	60.0	Aluminum
2.8	Excellent	64.3	
3.15	Extreme	68.3	

*$Ri = 100(1 - t_1/t_0)$.

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DRAWN PARTS

The final strain, or a total strain of all combined ironing operations, is calculated as

$$E_{\Sigma i} = E_{i-1} \times E_{i-2} \times E_{i-3} \times \cdots \times E_{i-n} \tag{9-46}$$

The approximate height of the ironed shell h_i may be assessed by using the formula

$$h_i = \frac{h_0 t_0 (D - d_1)}{t_1 (D - d_0)} \tag{9-47}$$

The pressure required for ironing increases with decrease of the die face angle, which is most often between 10° and 45°. An approximate calculation is given in Eq. (9-48).

$$P_i = \pi d_1 t_1 S_{\text{avg}} \ln \frac{t_0}{t_1} \tag{9-48}$$

where d_1 = mean diameter of shell after ironing
t_0 = shell thickness before ironing
t_i = shell thickness after ironing
S_{avg} = average value of tensile strengths before and after ironing, or $(S_{\text{before}} + S_{\text{after}})/2$.
ln = natural logarithm

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CHAPTER 10
PRACTICAL DIE DESIGN

10-1 BASIC APPROACH TO DIE DESIGN

With every new part produced, a complete evaluation of the stamping method and parameters must be performed. Based on the part's flat layout, the sequence of tooling must be designed, which in turn dictates the size of the die. The economies of the strip must be assessed before the rest of the design is finalized. Seemingly small details such as the availability of strip material, the predetermined width, and its thickness and tolerance ranges may turn out to be of tremendous importance when it comes to production.

For selection of the proper press, tonnage requirements must be calculated. Further, the amount of stroke, shut height, mounting arrangement, and other press- and production-related data must be compared to the capacities of the selected press equipment.

Only then may the actual design be started, which always begins with the strip layout and its projection into the cross section of a die. Such a sequence of work process is intentional, as the cross-sectional view provides control of the placement of punches within the assembly. Where punch bodies or heads may be too large to fit the predetermined sequence of operations, or where an additional station may need to be added later on, one of the stations must be skipped with subsequent enlargement of the die. This can be readily assessed by comparing the cross-sectional view with the layout of the strip, whereas by looking only at the strip this may pass undetected.

Both strip layout and cross-sectional view should be drawn to size or scaled. With accurately drawn punches and dies, the need for further detailing may often be eliminated. In questionable areas, some dimensions may be added instead of separate sketching or verbal explanations.

10-1-1 Strip Layout and Selection of Tooling

One of the main determinants in an assessment of appropriate strip layout is the production rate expected from the die. As already addressed in the first chapter, a situation where 100,000 pieces are to be delivered within a month is completely different from that where the same number of parts must be produced within a week or perhaps even a day.

To evaluate the problem of production rate properly, a rough estimate of the tonnage and die size must be made for selection of a suitable press. These are preliminary assessments and need not be based on elaborate calculations or sketches. A hand sketch of the strip will often suffice, showing only the sequence of tooling and its location.

Once a press of appropriate tonnage, bed size, stroke, and shut height is selected, scheduling of this machine has to be consulted to find out its availability. It is important to know what other jobs may be running at the time the new production is to begin, if such runs may

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be interrupted, or if a rigid schedule denominated by firm deliveries is to be observed. These aspects must be clarified before the new assignment is committed to the specific pressroom equipment, especially where the proposed die and its size, shut height, and other parameters may not fit any other machine. For an evaluation of the press availability in conjunction with press-room scheduling and other requirements, consult Sec. 1-2.

With flat parts, the stroke of the press should be of no concern, as their height is almost negligible. However, where bent-up parts, drawn shells, and other three-dimensional profiles are to be produced, the stroke must be adequate to clear their height, which in some cases may be excessive for the selected pressroom equipment.

With regard to the number of parts to be produced, an accurate strip layout should be drawn next. It will help to evaluate the correctness of the first rough assumption, and it will also establish the exact location of blanks within the strip. Parts may be positioned horizontally, vertically, or at an angle. They may be placed beside each other or intertwined.

Taking as an example the part shown earlier in Fig. 7-1, its vertically oriented placement within the sheet will be as shown later in Fig. 10-1. The amount of feed will be equal to the width of the part, plus a distance S_p between the blanks. Rules governing the distance between parts and their distances off the edge are presented in Table 6-6, Table 7-7, and Figs 6-31 through 6-33.

10-1-2 Economies of the Strip

With the width of a blank at 1.50 in. [38.10 mm] (Fig. 10-1), the feed, or the amount of progression of the strip during the operation of the die will be 1.593 in. [40.46 mm]. Evaluation of economical aspects of such an arrangement consists of comparing an area of the blank to the total area of the strip needed for production of such a part.

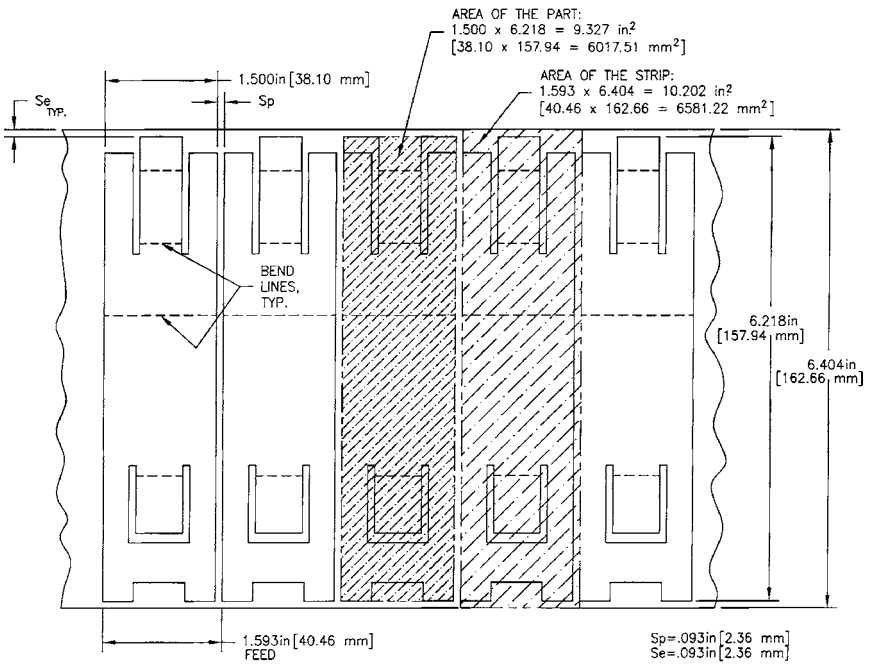

FIGURE 10-1 Vertical strip layout of the bracket.

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The area of the blank need not be calculated too exactly; its rough outline as indicated in Fig. 10-1 will suffice, provided the same method is used in all subsequent evaluations of differently positioned blanks.

The area of the part being 9.327 in.^{2} [6017.51 mm^2] and a corresponding area of the strip being 10.202 in.^{2} [6581.22 mm^2], can be used in calculation of the percentage of strip taken, along with the spacing between the parts, up by the part, as

$$100\ \frac{\text{part area}}{\text{strip area}} = 100\ \frac{9.327\ \text{in.}^2}{10.202\ \text{in.}^2} = 91.42\%$$

This means that the part, positioned on the strip per the arrangement shown in Fig. 10-1, uses up 91.42 percent of the area of the strip for its production. Such a high percentage rate is quite impressive, yet a different positioning of parts will often be evaluated for comparison.

The arrangement shown in Fig. 10-2 places the blank on the strip lengthwise. In such a situation, the feed is equal to the entire length of the part plus the spacing in between. The economic utilization of the strip, or the square footage, is calculated the same way:

$$100\ \frac{9.327\ \text{in.}^2}{10.648\ \text{in.}^2} = 87.59\%$$

The second strip arrangement uses up 87.59% percent of the strip area for its production. We may immediately observe that the second method of blank orientation is less economical. However, perhaps the result may be improved by sinking the *B* flange into the rectangular cutout of the next piece, should the flange be narrow enough to fit as shown in Fig. 10-3.

The economic evaluation of the square footage in such a case will be

$$100\ \frac{9.327\ \text{in.}^2}{10.279\ \text{in.}^2} = 90.74\%$$

The percentage of sheet usage is still less economical than that of the vertical strip, shown in Fig. 10-1. Naturally, decreasing the amount of material along the shorter side of the part will never produce results equal to those obtained by decreasing the material over the entire length, which is the case in Fig. 10-1.

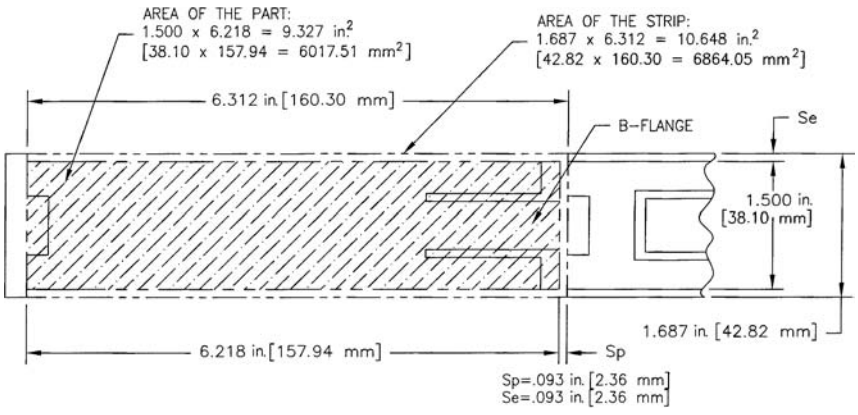

FIGURE 10-2 Horizontal strip layout of the bracket.

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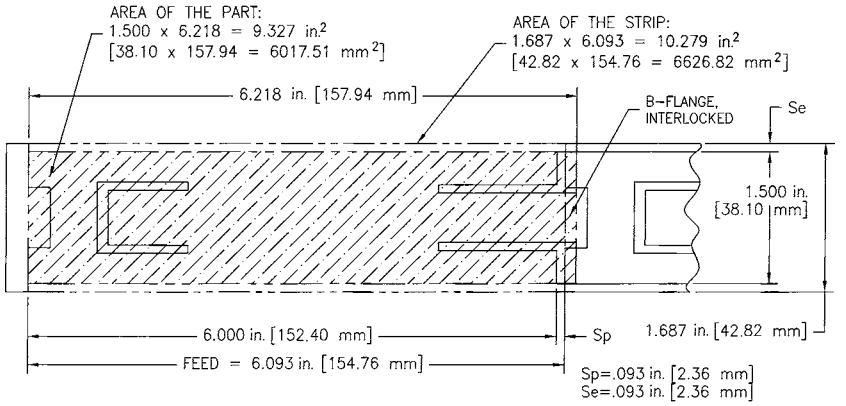

FIGURE 10-3 Altered horizontal strip layout of the bracket.

Quite often, not only the economies of the strip should be taken into consideration when evaluating a new strip layout. The design of tooling that is to produce the various cuts and its complexity must be taken into account as well. We may frequently find that where economies of the strip are overall favorable, the tool design to support such decision is more costly.

For example, if we consider the horizontal strip layout of the bracket presented in Fig. 10-3 for tooling, the shape of a parting punch (shown in Fig. 10-4) becomes more complex for manufacturing. Not only is such a shape more difficult to produce even in times of advanced EDMs; it is also more readily prone to chipping and breakage, demanding a more precise alignment between the punch and the die.

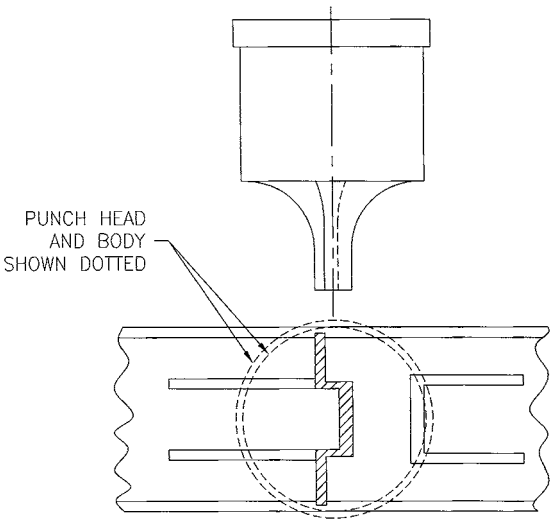

FIGURE 10-4 Single-hit parting punch.

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PRACTICAL DIE DESIGN

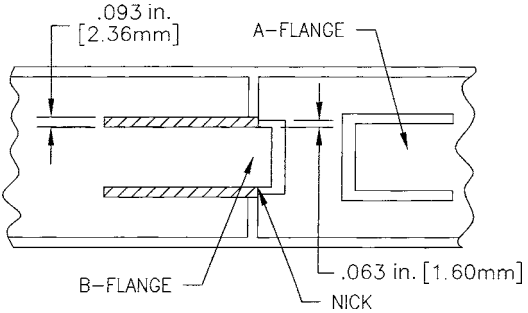

FIGURE 10-5 Trimming of the B-flange.

To replace such a tool is also more costly, as opposed to replacement of the few basic rectangles and squares that would have produced the part in Fig. 10-1. True, if single hits with rectangular punches would be used, these will demand at least one more station to be added to the die (see Figs. 10-5 and 10-7).

In Fig. 10-5, we are trimming the sides of the B-flange with two basic rectangular punches. This way we can easily cut out most of the material, with exception of the area where the B-flange becomes nested within the next part. Here the width of the metal to be removed shrinks from 0.093 to 0.063 in. [2.36 to 1.60 mm], which calls for either a step down in the punch width, or a termination of the cut.

In this scenario, we are ending the cut right where a different width begins. This approach is often more practical, even though by continuing with the cut along the B-flange side later on, we may produce a nick in its surface. This little notch will pass unheeded most of the time, but where dealing with a cosmetically demanding product, we do not want to

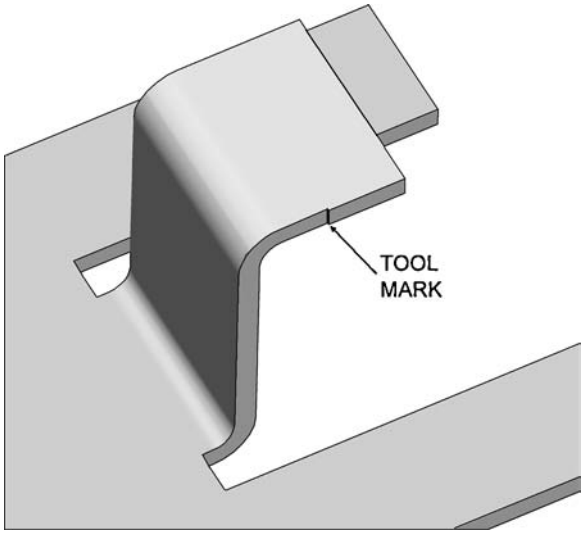

FIGURE 10-6 Tool mark in a formed flange.

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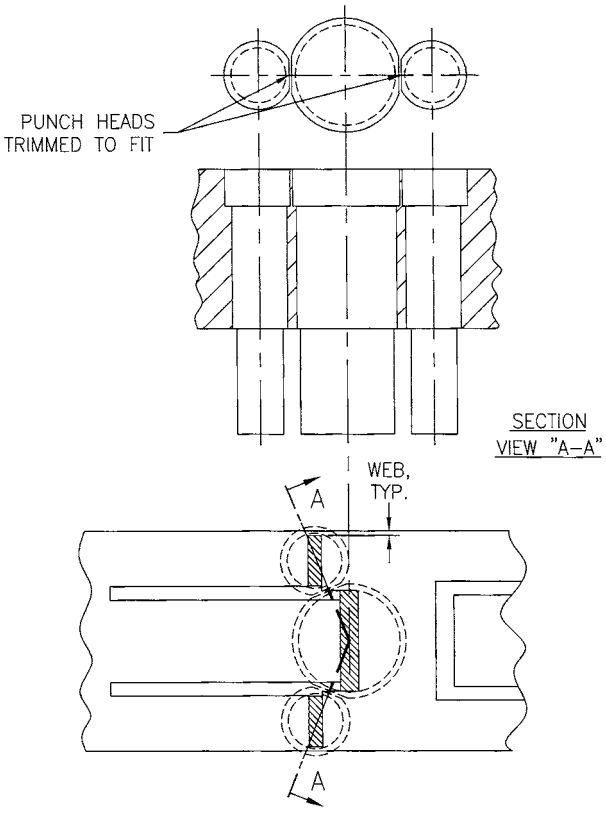

FIGURE 10-7 Final trimming with simple-shaped punches.

offend the eye of the customer with unsightly "nibbling" marks or tear the skin of the operator's hand with a notch in the part's edge (see Fig. 10-6). If such is the case, a step in the punch may be a better choice.

With this in view, Fig. 10-7 shows the final separation of the B-flange and a partial separation of the two side prongs, which all can be done with three basic rectangles. True, when we look at the section view A-A, we may observe that the heads of the three punches will certainly interfere with each other along the sectioning line, A-A. To solve this problem, the heads will have to be trimmed perpendicularly to the sectioning line A-A, which is also the line connecting the centers of these punches. Such a trim would not weaken the punches in any way, as plenty of head area for support will still remain.

At this time, we should mention the web, noticeable in Fig. 10-7. Such web is a narrow sliver of metal that keeps the parts connected to the strip, all the way up to the final forming or final cutoff station. In our case, the web is necessary, for the width of the part is equal to the width of the strip. Without the connecting web, the strip would have become dismantled. The web holds the strip together for the B-flange forming and provides support for the semifinished part to move into the last operation, where it is usually removed, along with the final forming.

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PRACTICAL DIE DESIGN

Another alternative to the B-flange final cutoff is presented in Fig. 10-8. Here we have the nicks in the B-flange sides, the tooling is also more costly than ordinary rectangles and squares, but the cut is fairly simple. Of course, the best way to solve the problem will be to redesign either the width of the B-flange, or that of the u-shaped upper recess to retain the same gap in between.

However, back to the basic flat layout and evaluation of the economies of the strip, we may quickly review the strip layout shown in Fig. 10-9.

Just by looking at the angular arrangement of the blanks we may conclude that such a strip layout is the most unreasonable of all. If calculation of a square footage is attempted at all, it should be done as a practice only.

This assessment leaves the strip layout presented in Fig. 10-1 as the best economical scenario of all the alternatives presented here.

There are additional factors to take into account when deciding between a lengthwise-running strip (as seen in Fig. 10-2) or a vertical strip layout (as in Fig. 10-1). The lengthwise positioned strip (sometimes called a *ribbon stock strip*) is harder to pilot, for the space for pilot holes is often minimal, or perhaps even lacking. The quantity of parts produced in any given interval will rarely match that of the vertically oriented part, which, when combined with the parts' greater inaccuracies, can often be detrimental to the whole product. Additionally, in long-spaced parts, the possibility of adding an extra station is often next to none.

With long parts positioned vertically (Fig. 10-1), a bow can be created and often is, as the coil often has such a deformity already implemented in its surface from the mill. This

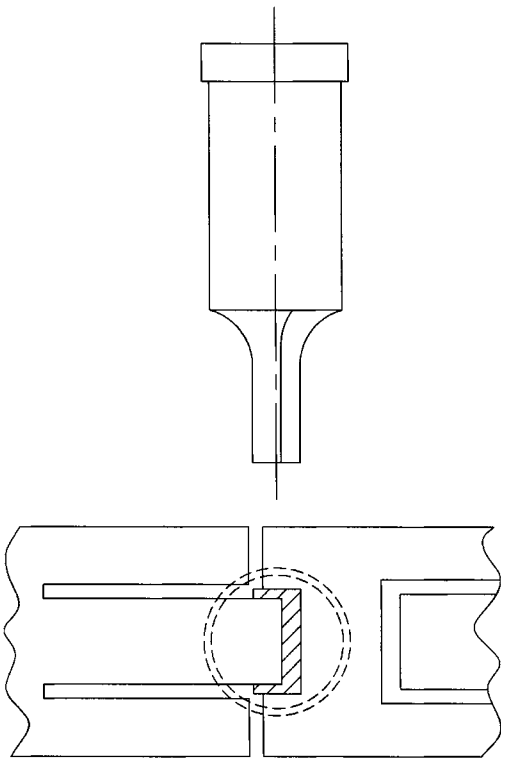

FIGURE 10-8 Alternative trimming of the B-flange.

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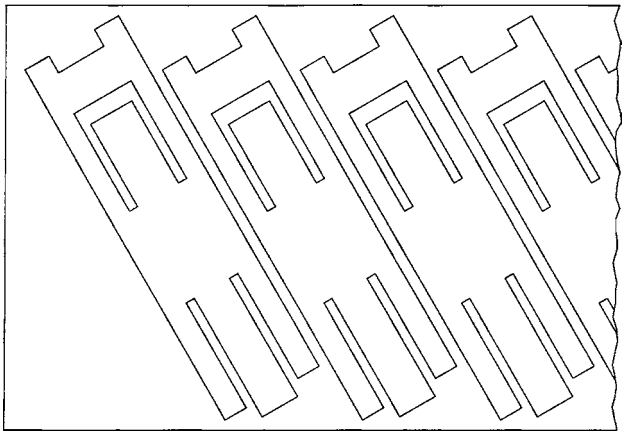

FIGURE 10-9 Angular strip layout of the bracket.

can be more readily eliminated in lengthwise-fed parts, where a straightener removes such a drawback before the strip enters the die.

Another disadvantage of long blanks positioned vertically is a so-called strip growth, where due to the shift in the lacy strip, the location of openings or the widths of parts can be found greater than the same distances measured off the die steel.

10-1-3 Tonnage Calculation and Selection of the Press

The next step is to verify the calculation of tonnage needed to produce the part. The total of all cut outlines as in Fig. 10-10 should be obtained by adding up linear distances of the part's periphery, the linear length of round or otherwise shaped cuts, notches, openings, and pilot holes. The total length of all cuts should be multiplied by the thickness of the stock and by the shear strength of the material in tons, presented in Table 6-4, "Shear Strength of the Material."

The tonnage needed to produce bends should be included in the calculation to procure the total of all tonnage needed to produce a complete part during each hit of the press. It should not be overlooked that even though piercing and bending is done in stages, it must all be accomplished within a single stroke of the press.

Another influential determinant in the choice of a press is the size of its bed area compared to the size of the die shoe.

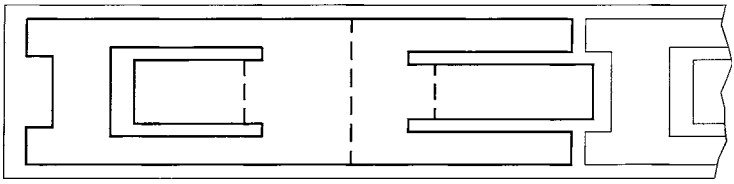

FIGURE 10-10 Tonnage calculation.

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PRACTICAL DIE DESIGN

As already mentioned in Chap. 5, the press tonnage and the bed size must be well evaluated before committing the die to production. Where the press bed size may be too great for the size of a die we intend to use, bowing of the steel of the press bed and that of the ram may occur, which in itself may ruin the alignment altogether. A press of too low a tonnage will certainly suffer when running over its force limits. These and other aspects, including, but not limited to die mounting, scrap removal, parallels existence, or lack of such, must be taken into account.

In our evaluation, we should not forget that every press can easily produce a good part with every single stroke, where a properly designed and properly allocated die is mounted in it. But where haphazard design, erratic planning, and sloppy production is the rule, the same press can produce scrap with every stroke, not talking about the danger to its own alignment, danger to the components of the die, and danger to the safety of the shop personnel.

10-1-4 Die Shoe Size

A thorough evaluation of the tooling sequence in conjunction with finalization of the strip layout is the next step to take. An accurate sketch of the strip provides overall dimensions of the die shoe, not only dimensionally but through a visual verification as well. The die shoe must be ordered with dependence on the suitability of its delivery, most often placing the order as soon as possible.

The evaluation of tooling sequence may often be accomplished by first establishing the method of bending the part. Of importance will be the location of a blank in the die, the direction of bending, and whether the part will be positioned up side down, or down side up. With many parts, such a decision will influence all the preceding die work, affecting the location of tools within either the upper or the lower portion of the die cross section.

The part from Fig. 7-1 as shown in Fig. 10-11 has two somewhat controversial tabs *A* and *B*. Their advantage is that both of them point in the same direction, while the remainder of the part is still flat. Therefore, with regard to the bending sequence, we may opt for producing these two flanges first. The sequence of all additional operations should then be arranged accordingly, to first produce these two flanges, with the final bending of corner bends *C* and *D* to be done in the last station.

The first bending method, corresponding with the above requirements, is shown in Fig. 10-12. Both *A* and *B* tabs are already there. The final bending takes place in the last operation, where the bending punch forces the part into the recess in a die. Bends *C* and *D* are formed simultaneously, and the finished product is ejected upward.

Notice the relief angle on the forming punch, which is geared to take the excess over 90°, should it occur. As shown earlier, coining of the edges or ironing of the bend sides can be implemented to solidify the bend. This bending can be done as shown, or upside down, with the same result.

Another bending method, shown in Fig. 10-13, utilizes wipe bending of the C-bend, combined with a cam action against the D-bend. A modification of the same process would be wipe bending and roller bending, or perhaps two rollers' bending.

Regardless of the method chosen, the bending should preferably be done in the last station, and the rest of the strip should be arranged around such a requirement. The choice of method is denominated mainly by the location of burrs. Where tabs *A* and *B* are bent down, burrs will usually be oriented around the outer surface of the part, whereas with tabs bent up, burrs may be found on the inside (refer to Fig. 10-11).

The strip layout in Fig. 10-14 shows the cutting and bending sequence, where all relief slots are provided in the first station, with the removal of the material of both edges in the second and fourth stations. On arrival of the part in the third station, *A* and *B* tabs are produced. The cutoff takes place between the fifth and sixth stations, and in the latter location

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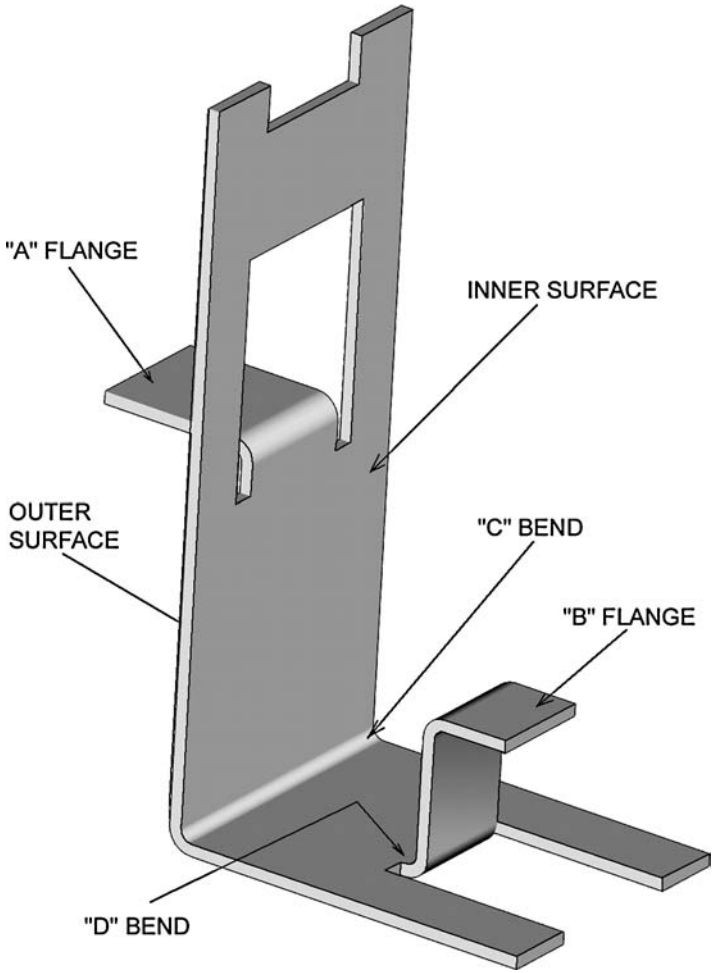

FIGURE 10-11 Bent-up bracket.

the final bending takes place. Finished parts are forced back—either up or down, depending on the bending method—to the die block surface level, from where they may be removed by air or allowed to drop down if the press is inclined.

According to the strip layout in Fig. 10-14, we have six stations within this die, spaced 1.593 in. [40.46 mm] apart, resulting in the total length of

$$6 \times 1.593 = 9.558 \text{ in.}$$

$$6 \times 40.46 = 242.76 \text{ mm}$$

Adding material to the sides and assuming 2 in. [50 mm] per side is adequate, in which case the size of the die block and punch plate will be approximately 13.625 in. [345 mm] long, and 12.50 in. [320 mm] wide.

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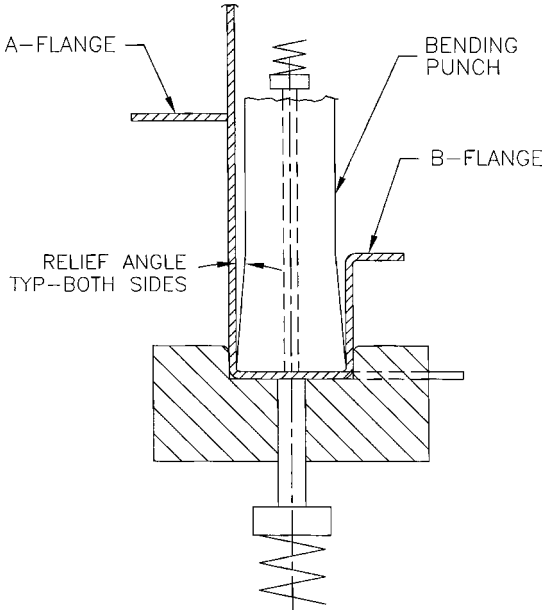

FIGURE 10-12 Bending of the bracket.

The size of the die block dictates the corresponding size of the die shoe. Here we refer to the manufacturers' tables and charts and find the appropriate die shoe combination. As already noted, the overall size of the die is of considerable importance, since it must fit the bed area of the selected press. Mounting of the die with regard to the mounting arrangement of the chosen press, along with all additional parameters, will have a definitive impact on selection of the proper die shoe.

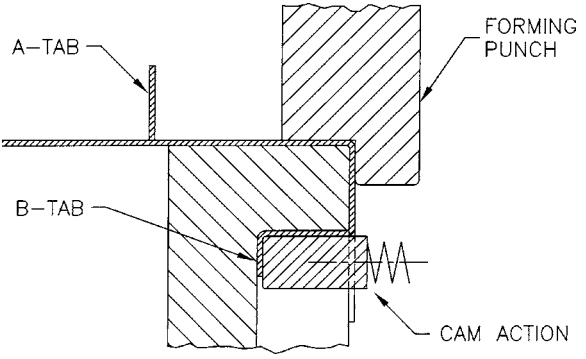

FIGURE 10-13 Wipe bending of the bracket, combined with cam action.

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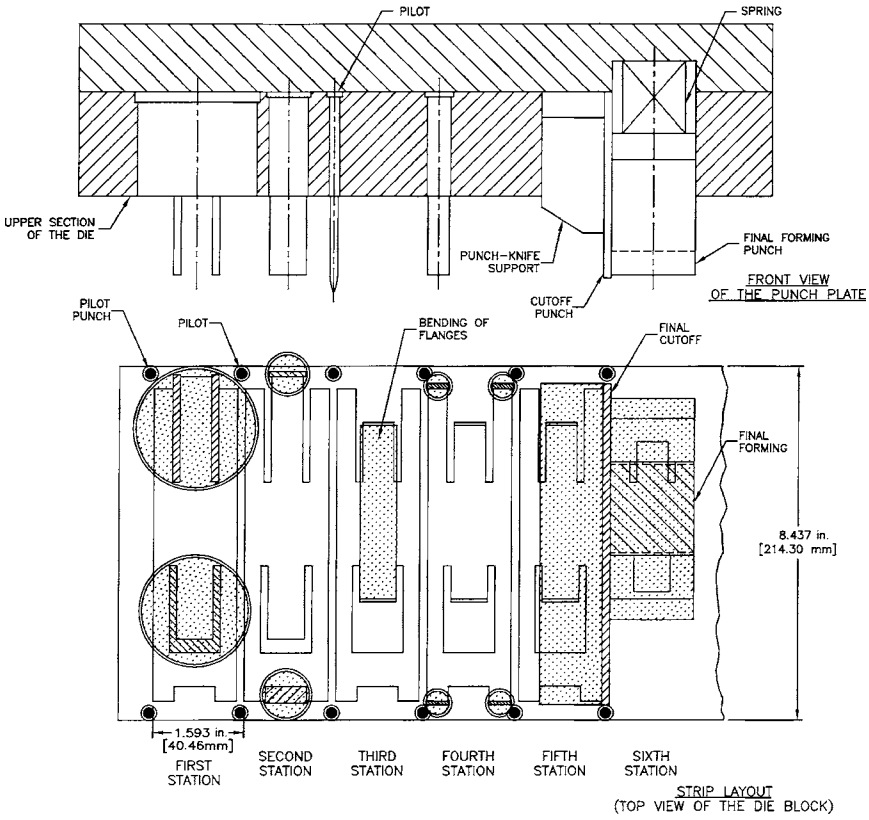

FIGURE 10-14 Strip layout and tooling. Cut shapes are shown as hatched, tooling bodies are dotted.

10-1-5 Method of Parts Ejection

The method of ejection of the part should be addressed, with checking into the ejecting system available to the chosen press. If the press bed is inclined, parts may be allowed to slide down off the die surface. Where parts are dropped through the bottom die shoe, the opening in the bolster plate of the press must be checked for size to evaluate if the parts will pass through in the location of the last station. Even where parts may fit when coming down straight, sometimes their passage may be impaired when turning haphazardly sideways, which may often be the case.

Where air ejecting devices are available, we should evaluate their usage with respect to the given shape of the part and see that the die design will incorporate the appropriate mounting openings to contain them.

The method of ejection, the arrangement of tooling sequence, and all previously discussed aspects should still be considered preliminary, as only the final strip layout, along with the accurate drawing of the cross section of the die, will show if parts can be produced as shown. These final details are addressed in the next chapter, which is reserved for such topics.

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10-2 PROGRESSIVE DIE DESIGN

As already noted, the overall production requirements are the main factors in considering the size of a die and the number of finished products per stroke of the press. Let us consider a requirement for 1,000,000 washers per week, to be produced in a press capable of delivering 150 strokes per minute. We may easily calculate that 150 hits per minute equals 9000 strokes per hour and 72,000 blows per workday. This means that if we run a strip through the die, producing one part with each blow, at the end of the week we will have 360,000 pieces.

However, we need a whole million of parts, which is 277.78 percent of whatever we are getting now. For that reason we should increase the output of a press by producing more than one part at a single stroke. To further shorten the length of production, we may want to build a die, producing four parts at a time, or a four-up die. The output from such a tool will certainly satisfy the basic demand, and there will still be some time left.

10-2-1 Washers and Other Round Blanks

With washers and other round blanks, the strip layout for a four-up die will look as shown in Figs. 10-15 or 10-16. The punches are not mounted along a straight line, as their shanks and heads will never fit the distance in between, aside from the fact that such a crowded arrangement will considerably weaken the punch plate and the die shoe.

Instead, the tooling is spaced along an angular axis, the angle of inclination off the horizontal being either 19.5° or 30°, which is an industry standard.

Such an arrangement gives us a comfortable distance between the stations for placing punches and dies without any interference. It also provides for the strip engagement along its whole width at the same time.

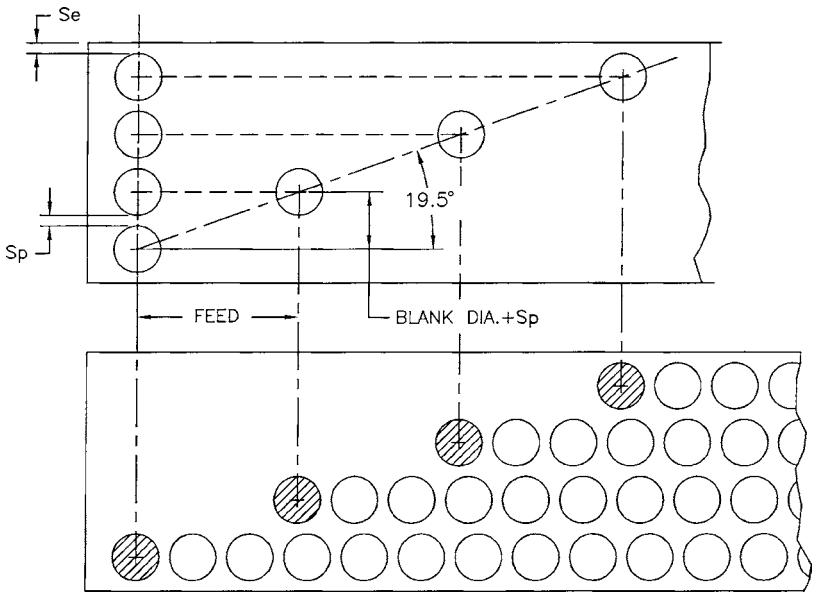

FIGURE 10-15 Strip layout for a round washer, 19.5° inclination.

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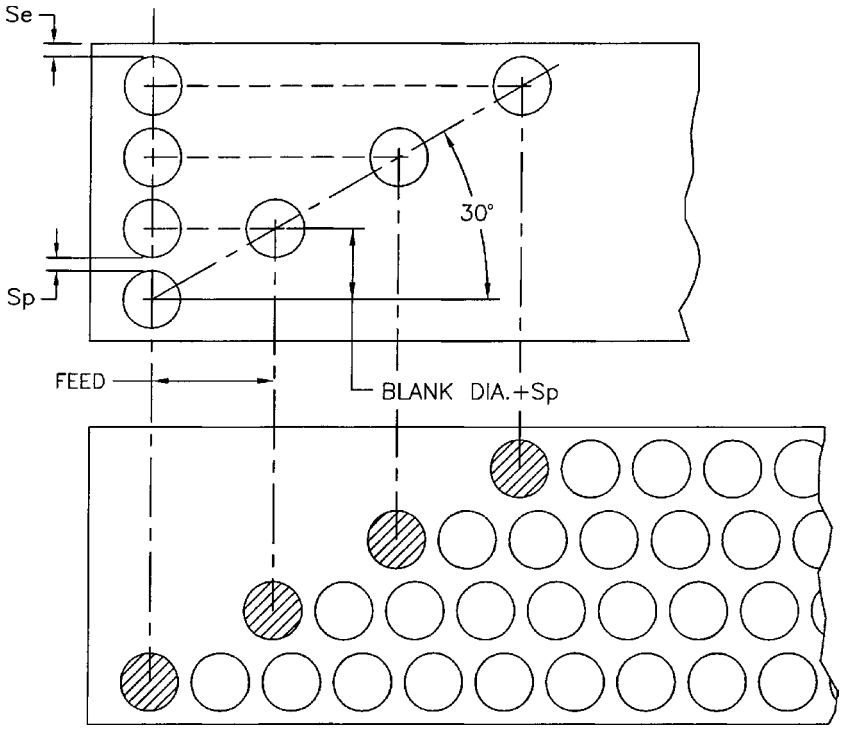

FIGURE 10-16 Strip layout for a round washer, 30° inclination.

The 19.5° strip inclination is shown in Fig. 10-15. The formula to use for calculation of the feed, or progression is

$$\text{Feed} = \frac{\text{blank dia.} + S_p}{\tan 19.5^\circ} = \frac{\text{blank dia.} + S_p}{0.354} \tag{10-1}$$

The 30° strip inclination is shown in Fig. 10-16 and the formula to use for calculation of the feed, is

$$\text{Feed} = \frac{\text{blank dia.} + S_p}{\tan 30^\circ} = \frac{\text{blank dia.} + S_p}{0.577} \tag{10-2}$$

Some additional guidelines and allowances pertaining to multiple-pieces strip layout are presented in the three illustrations by Arthur Seltmann, shown in Figs. 6-31 through 6-33.

As shown in Figs. 10-15 and 10-16, the first row of washers will be produced as indicated by their hatched shapes, with subsequent hits filling the area of the strip with an even and orderly pattern. The feed can easily be calculated by using the appropriate angle and figuring the vertical distance between the centers of blanks to be equal to the blank diameter, plus the required spacing S_p in between. These two values will give us all the additional data for the assessment of feed and strip width.

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10-2-2 Pilots and Pilot Holes

Every strip design should begin with an assessment of the location of pilot holes. These openings must be pierced at the first station, because they serve afterward as guides and locating arrangements for the strip on its way through the die.

Pilot holes may be extra openings placed beside the parts, or they may be holes included within the part itself and serving at the same time as the strip guidance. The location of pilot holes should always be at the far opposite sides of the strip, with the greatest possible gap in between. This is to secure the best fixation and positioning of the strip, once the pilots engage in their respective openings.

Pilot holes may not be necessary where producing complete parts from the strip in a single station of the die, as with production of washers, shown in Figs. 10-15 and 10-16. However, where any amount of subsequent work is to be done to the part, piloting of the strip must be included in the design of such a die.

The strip layout discussed in the Sec. 10-2-1 and shown in Fig. 10-14 may need to be reconsidered for more positive piloting and for less interference between the punches. Some may also judge this design a bit wasteful, as there is not much being done in the second and fourth station.

After rearranging the tooling around, the result can be seen in Fig. 10-17 with a sequence of material removal illustrated in Fig. 10-18.

Pilot holes are produced first on the new strip design, with pilots fitting into these openings right in the second station. At the first station, relief openings are produced in a similar fashion to that shown on the strip layout from the preceding chapter. However, the head

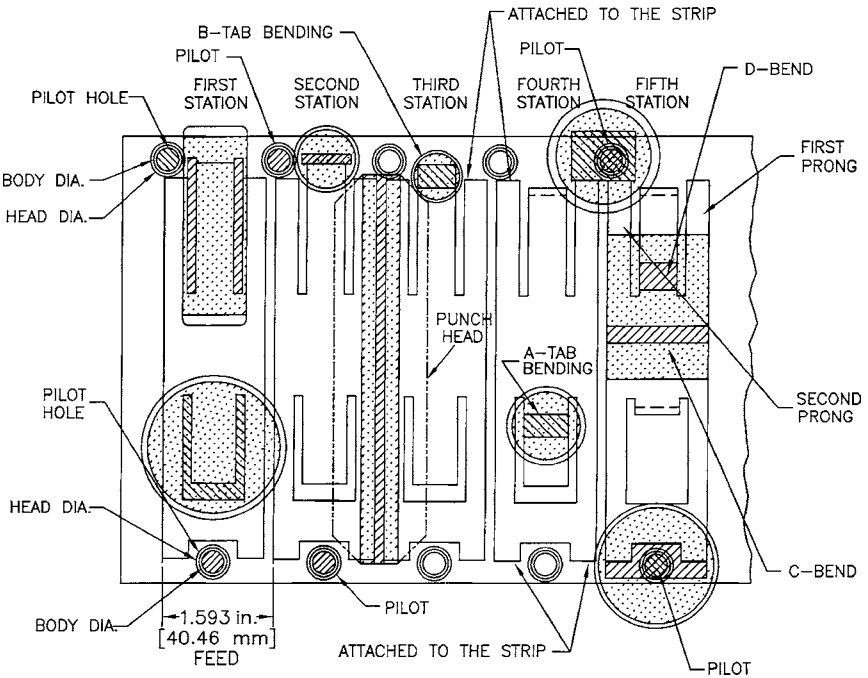

FIGURE 10-17 Strip layout of the bracket, adjusted but not finalized. Cuts and bends are shown as hatched; tooling bodies are dotted.

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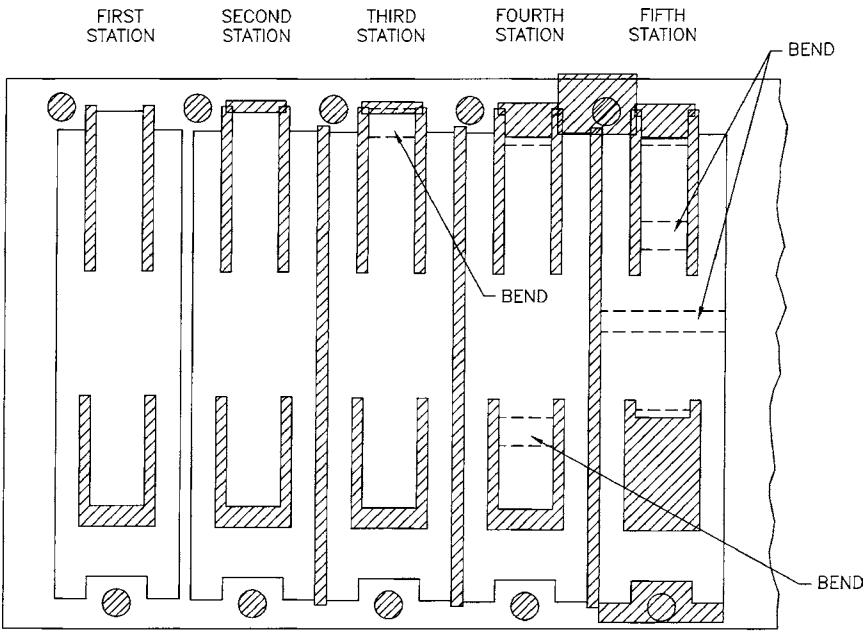

FIGURE 10-18 Cutting of strip-hatched surfaces are cutouts.

of the upper punch had to be altered in shape (from being round to rectangular); otherwise it would not fit between the two pilot punches.

The rectangular punch, removing the material from the bottom of the part, and used in the second station of Fig. 10-14, is moved into the last station. It is now different in shape, as it also replaces the two small punches from the fourth station, which were previously separating the two bottom prongs from the strip. In the middle of the new punch, a pilot tip is located. The two small horizontal punches removing the material attaching the two upper prongs to the strip in the fourth station are replaced with a single punch. This tool is also equipped with a pilot tip and positioned between the fourth and fifth station.

Lengthwise separation of parts is produced between the second and third stations, with bending of the *B* tab to follow and bending of the *A* tab to be achieved in the fourth station.

Within the final section, the part's total separation from the strip is produced, and bending of the *C* and *D* flanges occurs.

10-2-3 Skipping of Stations

Stations may be skipped or left nonoperative (empty) for various reasons. Where punch bodies or their heads may become excessive in size, resulting in interference between them, the station in between must be skipped.

In the first and second stations of Fig. 10-19 is a situation where such interference of the pilot head and that of the piercing punch occurs. Since skipping of the station will not help in either case, for the pilot will always be found in exactly the same spot, altering of its head will be the preferable solution, as shown in Figs. 10-20 and 10-21.

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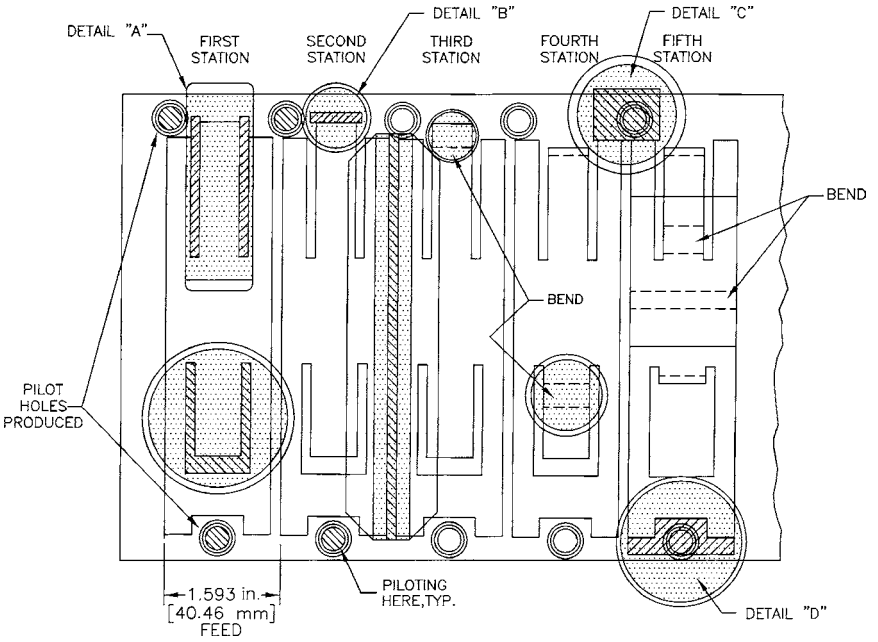

FIGURE 10-19 Strip layout of the bracket, detailed. Cuts and bends are shown as hatched; tooling bodies are dotted.

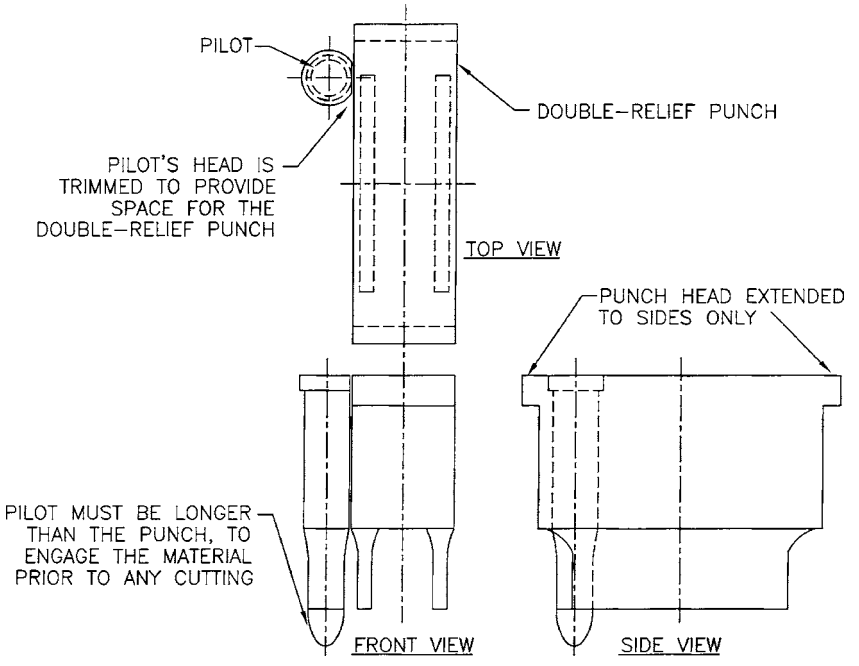
PILOT
DOUBLE–RELIEF PUNCH
PILOT'S HEAD IS TRIMMED TO PROVIDE SPACE FOR THE DOUBLE–RELIEF PUNCH
TOP VIEW
PUNCH HEAD EXTENDED TO SIDES ONLY
PILOT MUST BE LONGER THAN THE PUNCH, TO ENGAGE THE MATERIAL PRIOR TO ANY CUTTING
FRONT VIEW
SIDE VIEW

FIGURE 10-20 Detail A.

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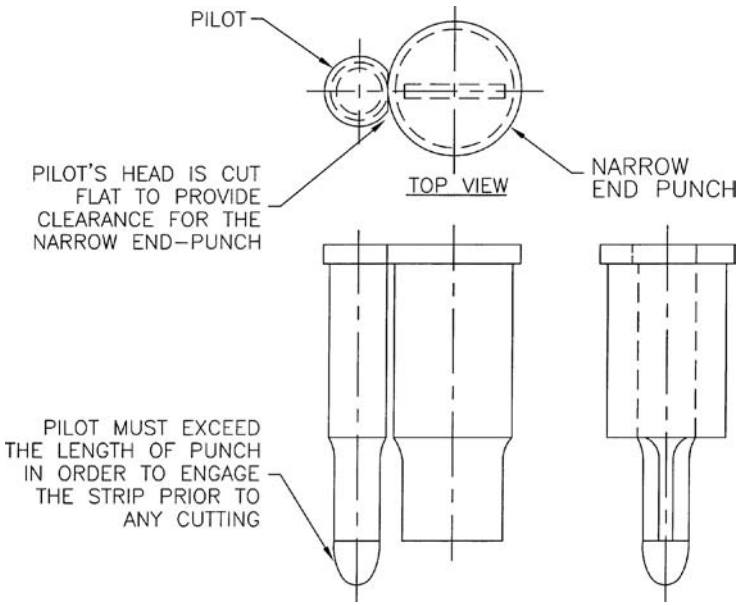
PILOT
PILOT'S HEAD IS CUT FLAT TO PROVIDE CLEARANCE FOR THE NARROW END–PUNCH
TOP VIEW
NARROW END PUNCH
PILOT MUST EXCEED THE LENGTH OF PUNCH IN ORDER TO ENGAGE THE STRIP PRIOR TO ANY CUTTING

FIGURE 10-21 Detail B.

Tooling details *C* and *D* (Figs. 10-22 and 10-23) have pilots installed within their bodies to provide for locating of the strip prior to any cutting. The pilot point must always exceed the length of all cutters, so that a proper location is attained prior to any alteration of the strip.

Another reason for skipping stations is a situation where the punch (or die) block is too densely perforated by too closely spaced tooling. An extensive drilling of these blocks will impair their strength, which should be prevented by spacing the tooling farther apart.

10-2-4 Nesting and Locating

Nests or relief openings of parts is required where the part shape is other than flat. With flanges bent down in one station, all subsequent stations must be provided with a relief opening to contain them not only on arrival of the strip into that particular station but also throughout their passage through the rest of the die.

Nesting of parts is further necessary where some highly accurate work is done to the part, for example, shaving. In such a case, the nest often contains the whole outer shape of the part, serving as a retaining and positioning device at the same time, for the ensuing die operation.

Some nests may consist of pins within the block, in between which the part fits, when deposited by the movement of a strip. Other nests are obtained by cutting the outline of the part into the solid block, where also the depth of the placement is controlled. Nests may also be made of segments Fig. 10-24.

A method of carrying a strip of sheet metal from station to station and performing various alterations to it is sometimes called the "cut and carry" method. It is a standard procedure of strip movement through the progressive die.

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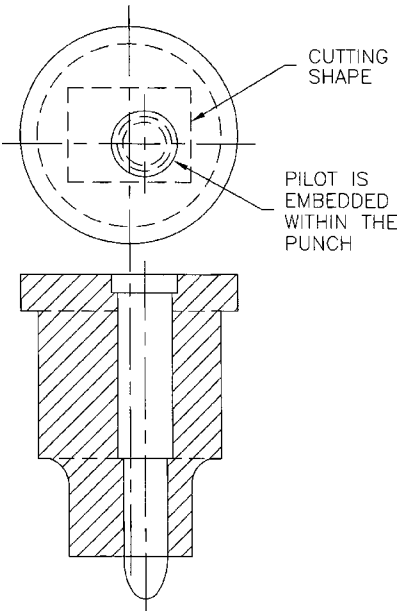

FIGURE 10-22 Detail C.

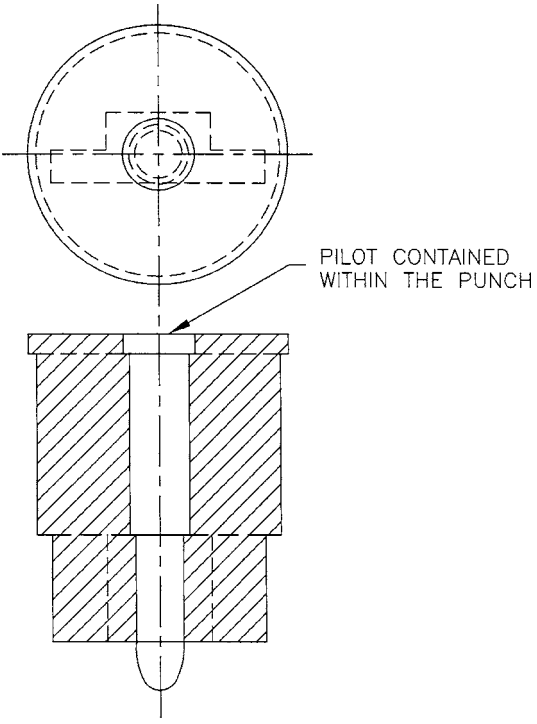

FIGURE 10-23 Detail D.

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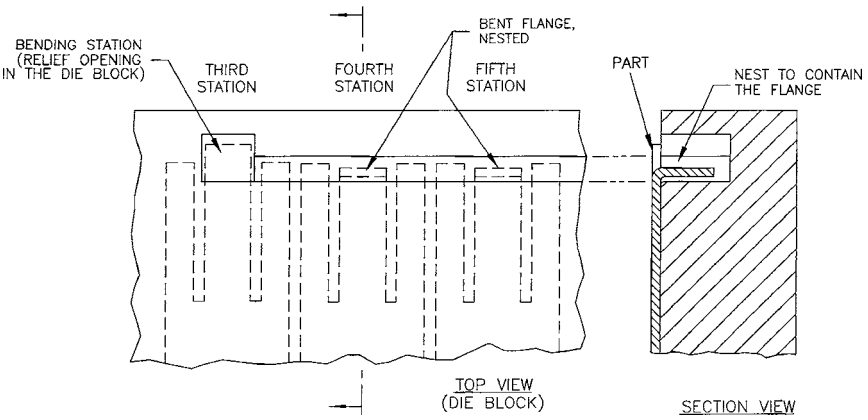

FIGURE 10-24 Die block with a relief channel.

10-3 SAMPLES OF DIE DESIGN WORK

As in every field, man learns the most by observing others and contemplating the ways he or she would have approached the given problem. There is no simple, one-shot solution to any task; there are always other possible methods and means of getting the most from the situation, the conditions, and the surroundings. Some such examples of different die design tasks and their solutions, are presented below.

10-3-1 Sample Strip Producing the Cover

A part, shown earlier in Fig. 7-9, was altered for the die production, with its phantom flange removed. The adjusted and simplified flat layout is shown in Fig. 10-25.

Positioning of such blanks on the strip may be as shown in Fig. 10-26. Here the pilot holes and 0.343-in-diameter [8.70 mm dia.] openings are produced in the first station, along with the two long relief slots. In the second station, the middle flange is severed off the

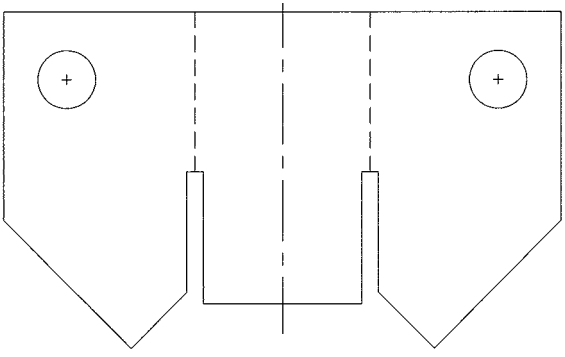

FIGURE 10-25 Cover, simplified flat layout.

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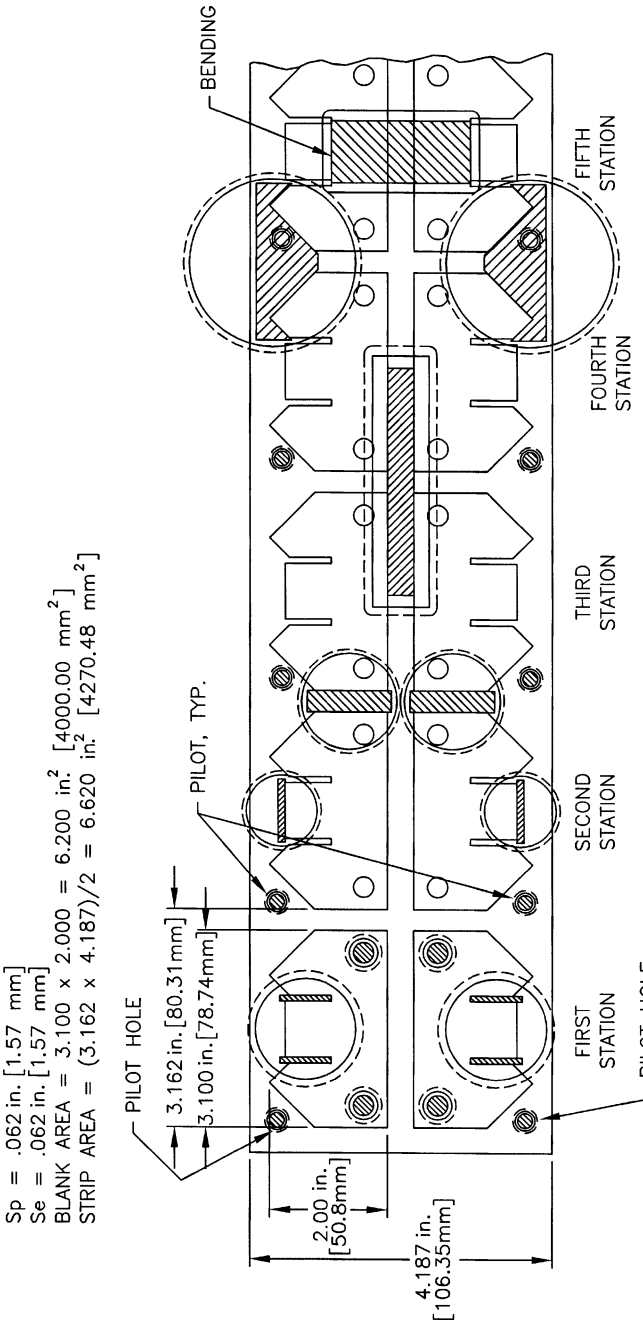

FIGURE 10-26 Cover, first strip layout.

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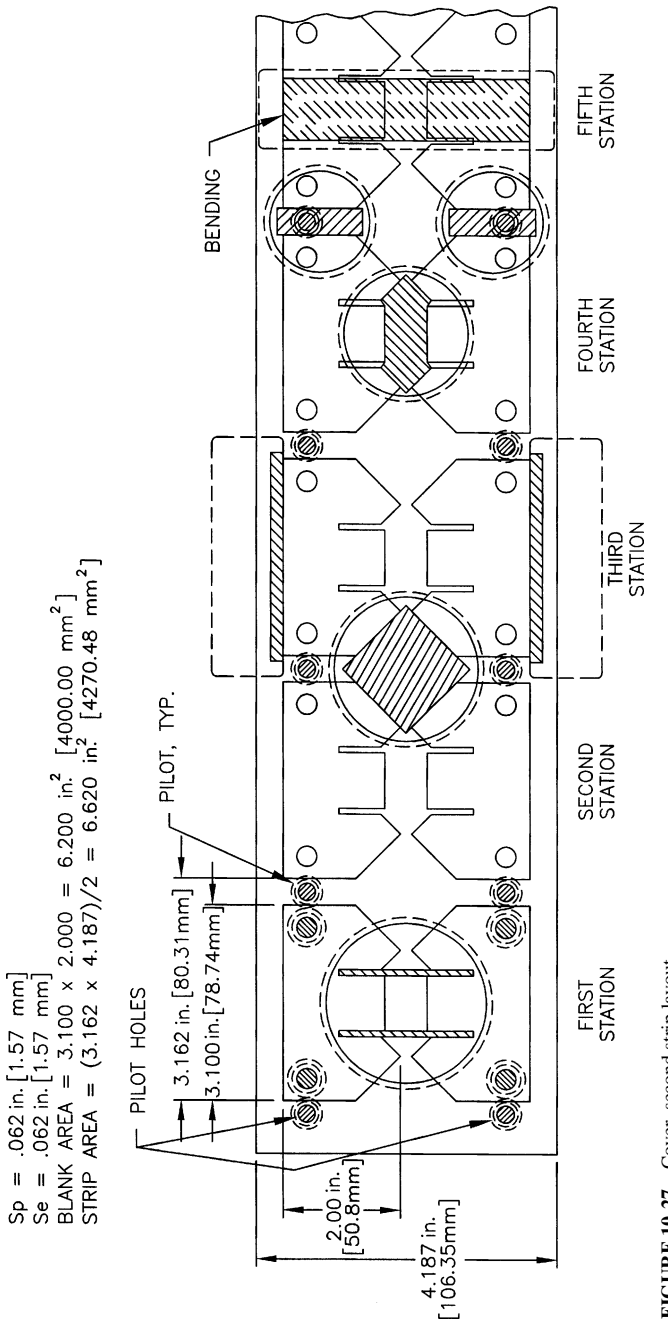

FIGURE 10-27 Cover, second strip layout.

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PRACTICAL DIE DESIGN

strip, and the side flanges are separated between this and the next station. The third and fourth stations share the long rectangular back-line cut, where the second half of the material of the third blank is removed at the same time as the first half of the material of the fourth blank.

Between the fourth and fifth station, all angular sections of side flanges are cut off, and bending is then performed in the last, fifth station.

When assessing the strip layout in Fig. 10-26 for the economy of such positioning, only a rough outline of the part may be calculated, provided that the same approach is used in all subsequent evaluations. In order not to break through the edge of the strip, the usually recommended S_e distance will probably have to be increased, yet for the sake of practice, the originally recommended 0.062 in. [1.57 mm] will be kept here. With the area of the part being

$$3.100 \times 2.00 = 6.200 \text{ in.}^2$$

$$[78.74 \times 50.80 = 4000 \text{ mm}^2]$$

and the area of the strip

$$(3.162 \times 4.187):2 = 6.620 \text{ in.}^2$$

$$[(80.31 \times 106.35):2 = 4270.48 \text{ mm}^2]$$

the square foot percentage will be

$$100 \frac{6.200}{6.620} = 93.65\%$$

However, such a strip layout presents a definite disadvantage in the fact that all tooling will have to be provided twice. This is caused by the mirror-image reversal of the part, which prevents almost any conjunction in tooling arrangement. Where a rather simplified method of tooling order is required, the parts should be as positioned on the strip, shown in Fig. 10-27.

The economical aspects of this strip layout are identical to Fig. 10-26. But where the tooling previously had to be different for each row of parts, here it may be combined, which may produce savings.

In the first station, the two pilot holes and two round openings are pierced simultaneously with the two long relief slots. Between the second and third stations, the angular material of the side flange is cut off, freeing one edge of each part with a single hit of a square tooling.

The third station provides for the removal of the long back strip of material; in the fourth station, the middle section is eliminated.

The web between the two parts goes at the transition between the fourth and the fifth stations. The tool used for its removal is basically a rectangle, with a pilot tip attached to its face by a threaded shank.

By cutting the web between, the final blank is separated from the strip, and all forming is provided in the last, fifth station. It should be noted that the forming punch is slightly shorter in order to finish cutting of the side web before any forming takes place.

The strip layout, as positioned on the die block, plus the cross section of the die are shown in Fig. 10-28.

10-3-2 Sample Strip of a Support Bracket

Shown in Fig. 10-29 is another blank, already discussed in the preceding chapter. Its positioning within the strip is rather awkward, leaving large areas unused and the economical evaluation of the square footage showing the blank as occupying only 48.82 percent of the strip area.

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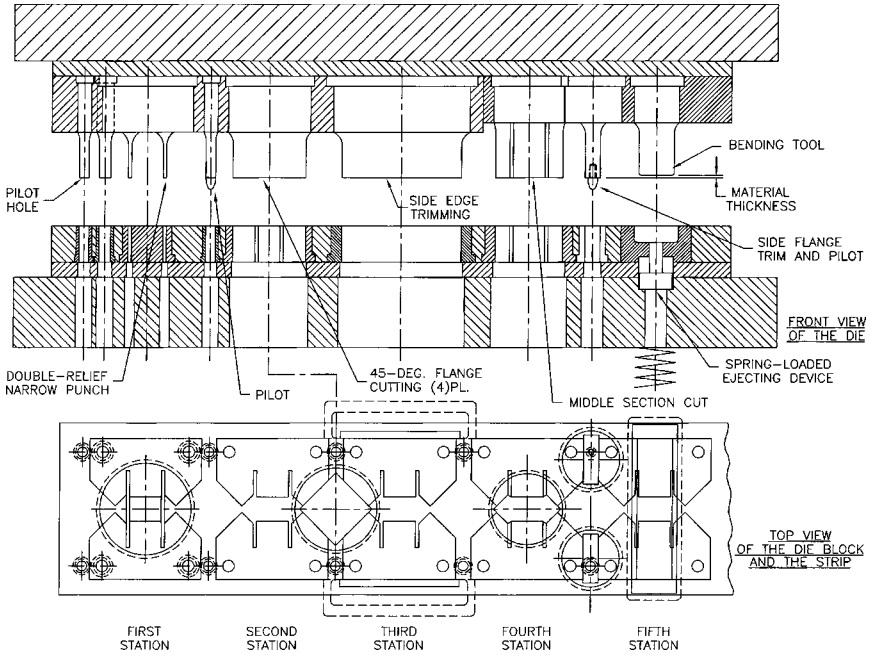

FIGURE 10-28 Cover, die layout.

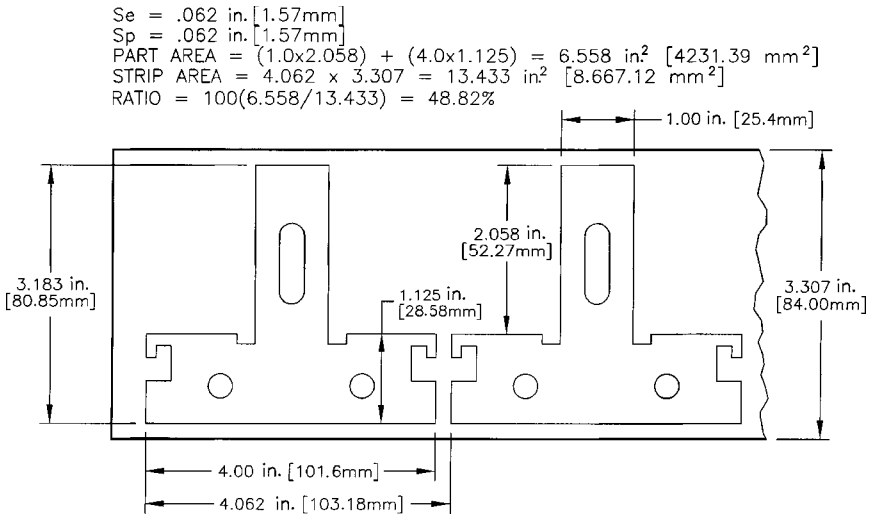

FIGURE 10-29 Support bracket, first strip layout.

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Utilization of the strip area is improved in the subsequent illustration. Shown in Fig. 10-30, the two interlocking parts show the area usage to be at 60.44 percent. This ratio is further enhanced by the strip layout in Fig. 10-31, where the square footage is 71.84 percent. But the final solution, presented in Fig. 10-32, with the square footage of the blank at 78.3 percent, seems to be the ultimate method of strip layout.

However, there are several problems with the winning strip layout, not obvious from the first fleeting glance. Most of the tooling to produce this part will have to be doubled, or rather quadrupled, because of the mirror-image reversal of the part. Therefore, we will have specialized tooling for removal of the material in section *A1*, with the same shape of tool, rotated at 180° to be used for removal of section *A3*. The same shape further rotated is used to cut *A2*, and an additional rotation will have to be produced for the removal of section *A4*. Yet, there is not a chance of using a single tool twice or combining it with another shape.

The same applies to the removal of material within areas *B1* and *B2*. All these shapes are identical; they could be punched with the same tooling, but their mirror-image reversal prevents such a practice, and each shape will have to utilize its own tooling at a different location, as well as rotated around its axis.

The strip layout of the blank placement per Fig. 10-32, with its respective tooling, is not provided. However, if such a sketch is attempted, it will certainly consist of at least 11 stations, which will make die design of such a size quite prohibitive. Just imagine, with the feed of 5.125 in. [130.18 mm] the linear span of 11 stations will amount to some 56.375 in. [1431.93 mm]. This is quite a size for a die, and such a tool will probably never be made just because of that.

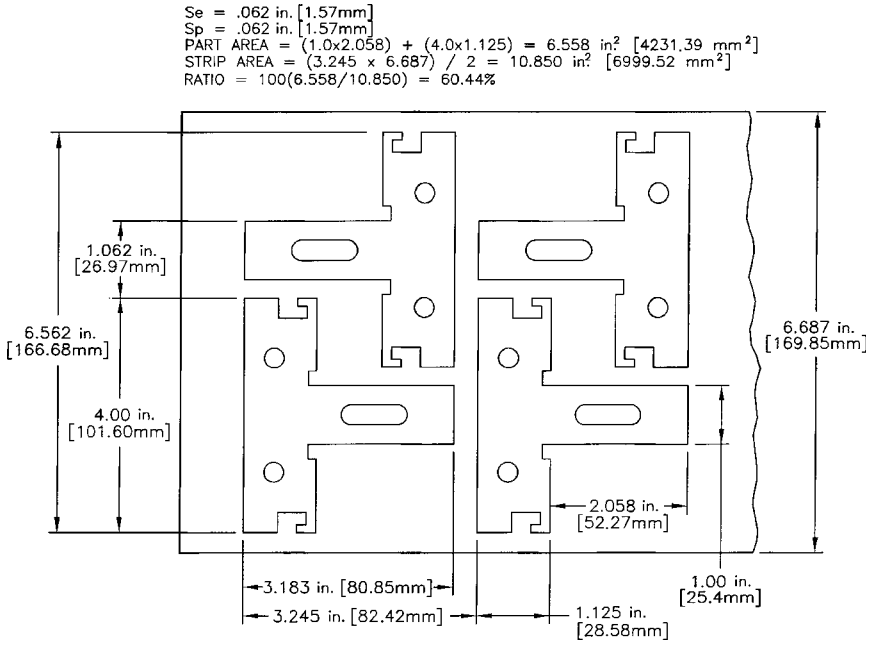

FIGURE 10-30 Support bracket, second strip layout.

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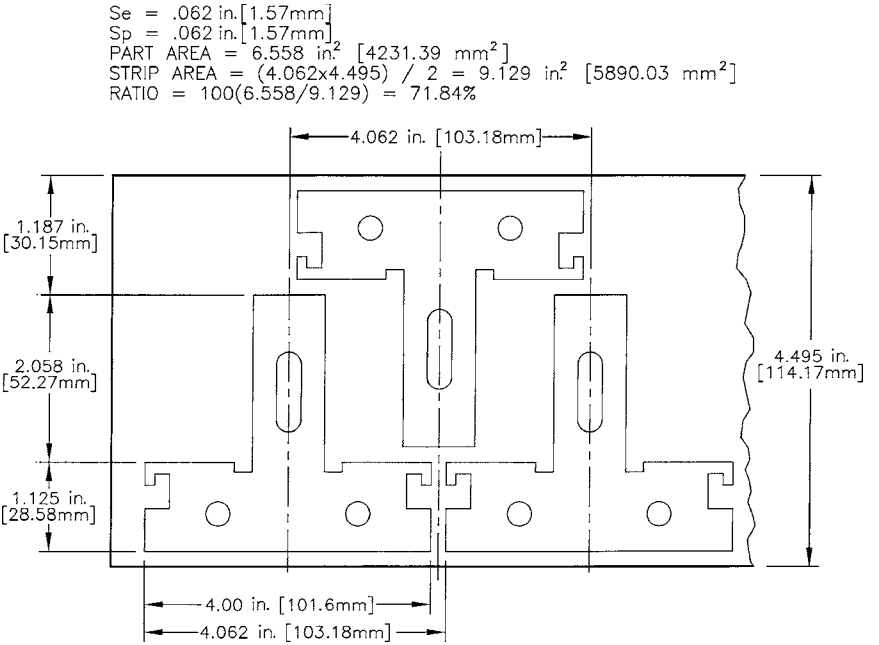

FIGURE 10-31 Support bracket, third strip layout.

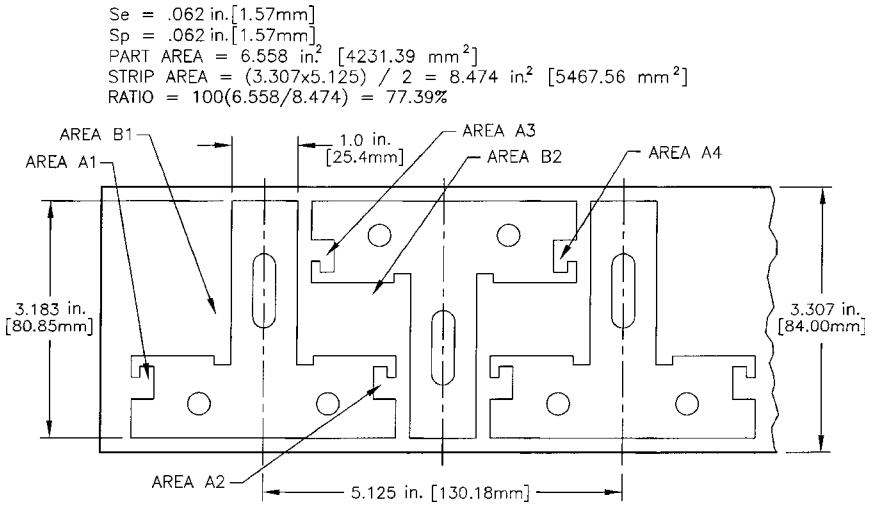

FIGURE 10-32 Support bracket, fourth strip layout.

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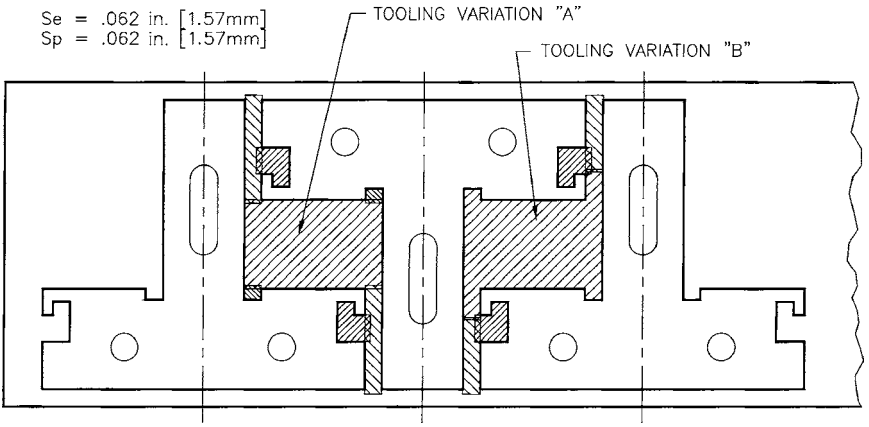

FIGURE 10-33 Fourth strip layout with tooling; tooling variation A and B.

Nevertheless, some tooling attempts are contained in the following illustrations, beginning with Fig. 10-33. An avid reader may try to sketch such a strip layout at his or her leisure.

Two tooling variations are presented in Fig. 10-33, each applied to one half of the part's outline. Method A uses two small squares and one large rectangle, in combination with two additional rectangles to remove the material between the parts. Method B depends on special-shaped large tools, supplemented by two rectangles.

Tooling variation C in Fig. 10-34 uses two large-sized rectangles and one square. In tooling variation D, a single specialized punch is used for removal of all the metal. Such tooling uses less hits to produce all cuts and will be needed in quantity of two punches and dies for the entire strip. However, its special contour will be more complex to produce and maintain than simple basic rectangles and squares.

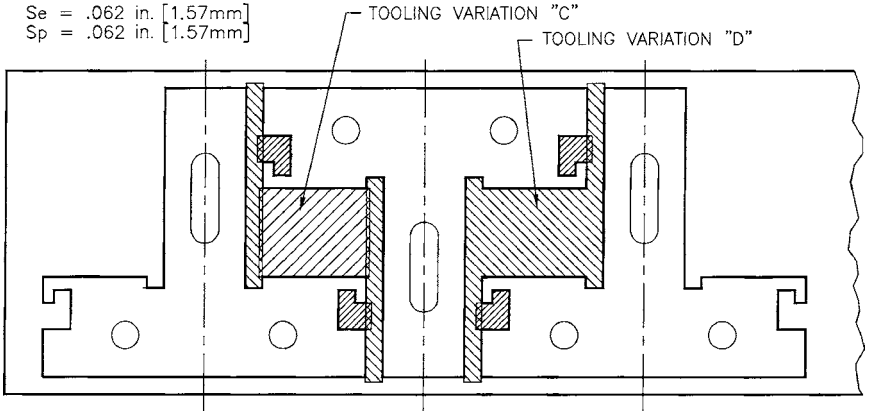

FIGURE 10-34 Fourth strip layout with tooling; tooling variation C and D.

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And so, at the end, we may even come back to the original, economically least effective strip layout, presented in Fig. 10-29. Its advantage lies in the fact that the parts are positioned the same way, which means that all tooling will be only doubled instead of quadrupled.

Further, such a layout may even be of advantage in cases where an additional, different part may be produced by utilizing the empty area, unused by the bracket pictured. If this is the case, the additional blanks may either be produced within the same die, or the strip may be run twice: once as shown and a second time with a different strip layout and in a different die, utilizing the remaining material.

Often, the reversal of the strip and running it through the same die may achieve the economies of the strip layouts shown in Fig. 10-32, while using a single set of tooling to produce the parts.

However, coming back to the original layout shown in Fig. 10-29, tooling variation *E* presented in Fig. 10-35 severs the part's outline off the strip with 2 hits per part. Tooling variation *F* needs also 2 hits, but such a method leaves no material in between to be utilized for production of different parts, unless the rectangular blank itself is the part.

Tooling variation *G* in Fig. 10-36 needs 1.5 hits to achieve the same, whereas variation *H*, using a specialized punch, produces the same result with a single blow. The ultimate solution of material removal is the huge tool shown in Fig. 10-37, which removes all the material with a single hit of a punch. It remains to be seen if such an approach is desirable.

10-3-3 Stainless Steel Spring

Looking at the die strip, the two D-shaped cuts are produced first (see Figs. 10-38 through 10-40), with the second D-shape mirroring the image of the first. It may be reasoned that a single hole should take care of the two openings in one hit, but on observation, the shape is not round and for that reason, a slightly oval punch would be needed (see also Fig. 10-40, detail "P"). A round cut will also divide in half the section between the pieces, which is, three stations down, removed with a long, rectangular punch. There will be two single slugs entering the die of that station, should a separation be achieved, which may cause problems all the way down to the scrap bin.

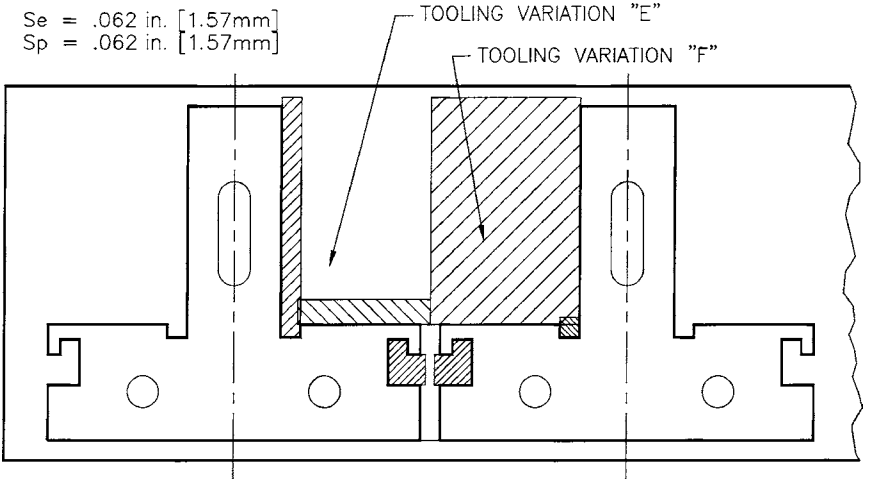

FIGURE 10-35 First strip layout with tooling; tooling variation E and F.

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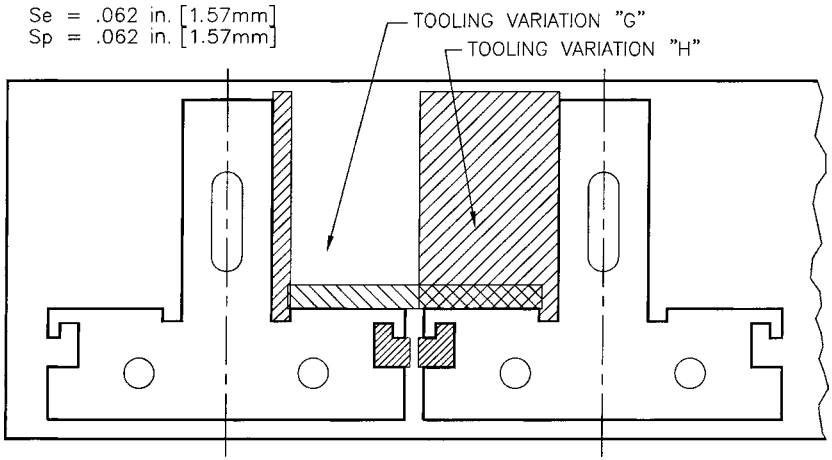

FIGURE 10-36 First strip layout with tooling; tooling variation G and H.

The two holes used for piloting of the strip through the die are provided in the same station. A long, rectangular cut separating each two parts follows after the third set of pilot holes. If this cut were to be made prior to the two D-shaped cuts, the toolmakers would have had hard time to generate such a small sliver of a tool, only 0.031 in. [0.79 mm] wide (see Fig. 10-40, details "P" and "R") and its breakage rate would be enormous. With the existing die arrangement, the D-punch is engaging the metal with the whole area of its face, which will produce no damage to the long rectangular punch when following afterward.

Next, after skipping three stations because of the size of tooling, the outer end of the spring is rounded, getting rid of that end of the strip at the same time. The springs, their long shapes not restricted there anymore, can be bent up. First, the shallow bend up is produced (i.e., *First Form*); next, the partial joggle down is made (i.e., *Second Form*). The final form and cutoff are quite simple, as shown in detail in Fig. 10-43.

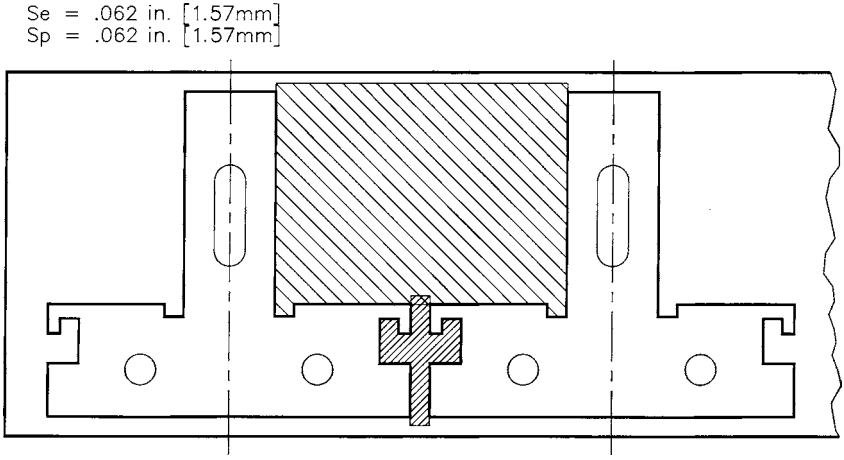

FIGURE 10-37 First strip layout; final tooling variation.

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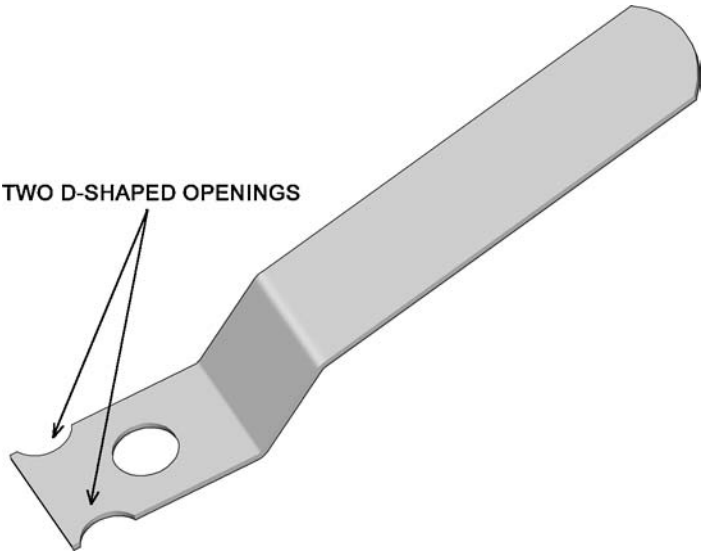
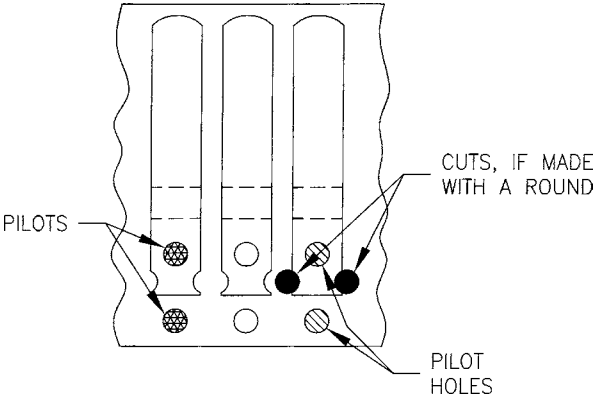


a. SPRING



b. TOP VIEW OF THE DIE

FIGURE 10-38 Stainless steel spring. (*Reprinted with permission from Standard Motor Company, Long Island City, NY. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

At the beginning of the die, shown on the the cross-section "A-A" in assembly, Fig. 10-40 and in a detailed view in Fig. 10-41, the stock pusher is seen as leaning against the material to keep it in place. The two pilots are fully engaging the strip prior to the long separating cut, which removes everything in between. In cross-section "B-B" (Figs. 10-40 as an assembly and 10-42 in detail), the first forming punch is shown. The whole assembly is guided by heavy-duty guide pins. Down stop pillars, upper and lower, protect this section from over-travel of the die.

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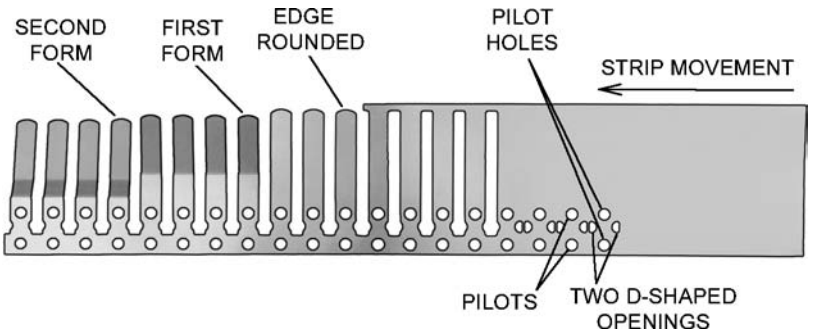

FIGURE 10-39 Die strip of the spring. (*Reprinted with permission from Standard Motor Company, Long Island City, NY. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, NJ. Reprinted with permission.*)

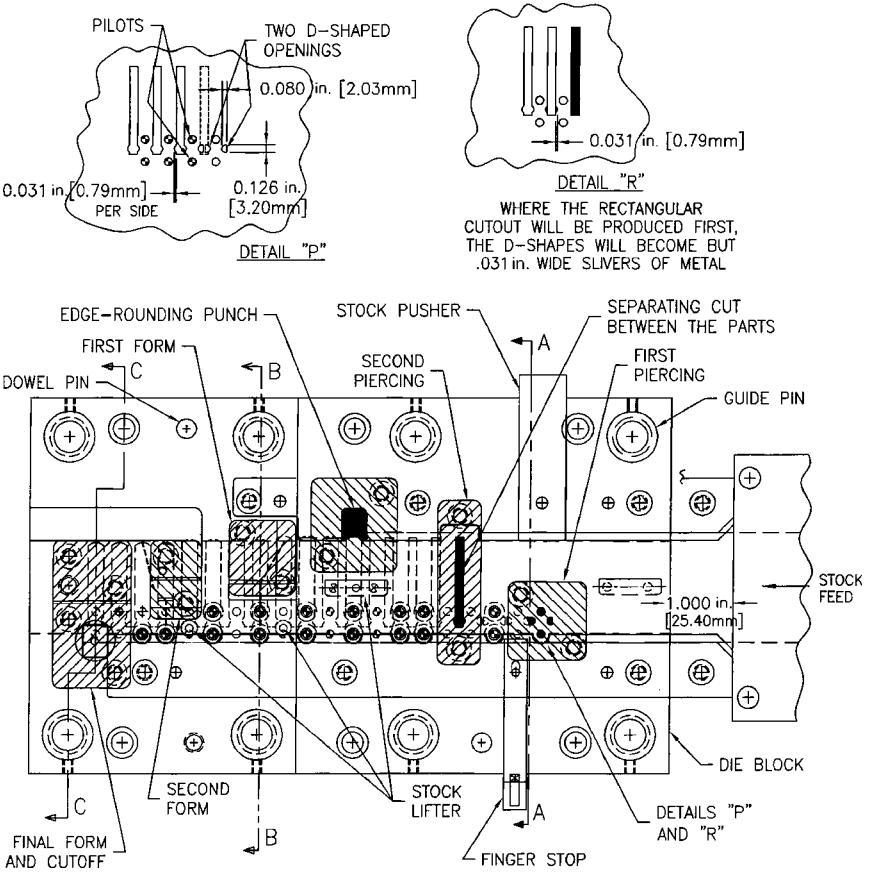

FIGURE 10-40 Die block. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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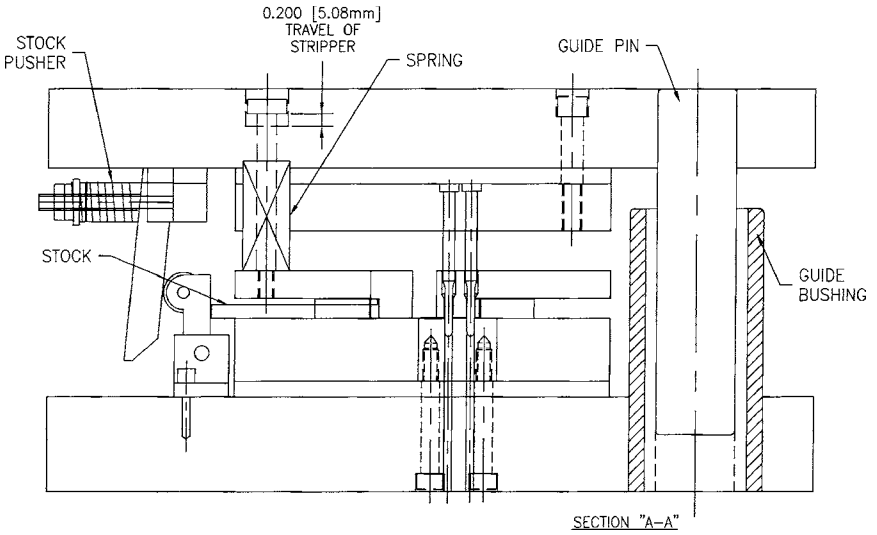

FIGURE 10-41 First piercing station. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

In section "C-C" (Figs. 10-40 and detailed 10-43), the cutoff punch has an interesting shape from which is obvious that it is timed: first, one portion of the part is cut off, with the remaining section following right afterward. Heavy guidance of die elements combined with step downs for prevention of damage to the die can be observed.

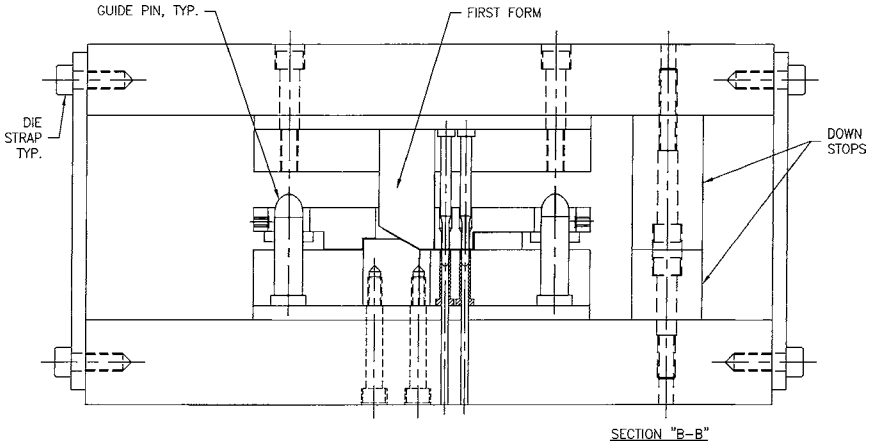

FIGURE 10-42 First forming station. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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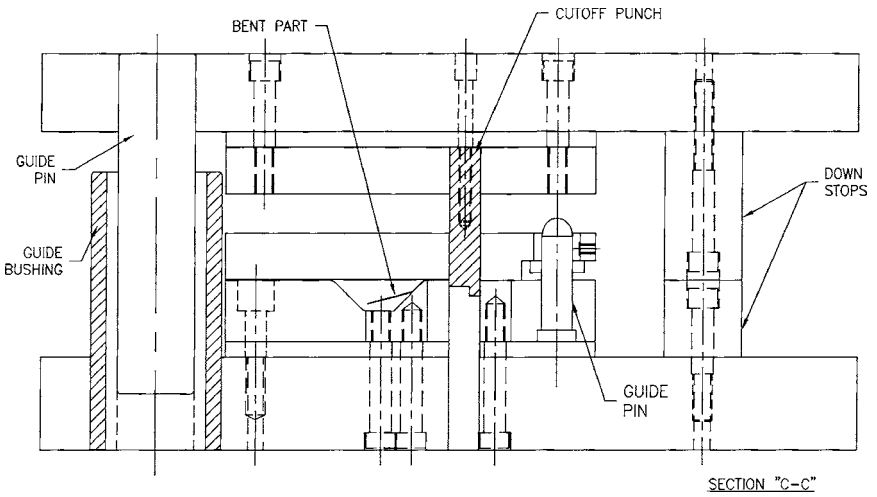

FIGURE 10-43 Cutoff of the part. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

10-3-4 Stainless Steel Contact Bracket

The shape of the centrally located tab is a bit tricky, as the tab is not only bent down (see Fig. 10-44); additionally, the tip at the end of a large-radius bend is formed under slightly less than 90° (see Fig. 10-45).

From the die strip (Fig. 10-46) we can read that the holes in the sides were provided first, along with piloting holes, one per each side. A partial cut removing the material around the centrally located tab is performed in the next station; the whole tab is cut free in the following station. This being done in two steps was for the purpose of not weakening the die section.

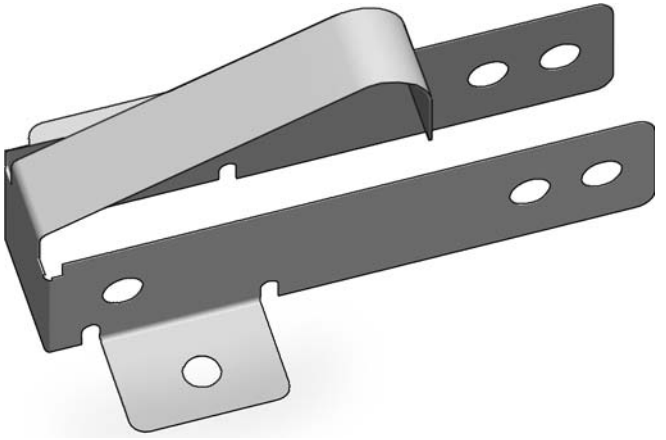

FIGURE 10-44 Stainless steel contact bracket. (*Reprinted with permission from Roselle Tool and Die, Roselle Park, NJ.*)

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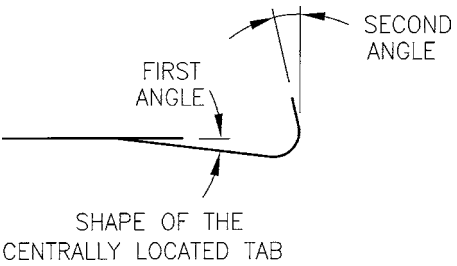

FIGURE 10-45 Centrally located tab. (*Reprinted with permission from Roselle Tool and Die, Roselle Park, NJ.*)

Forming section, which shapes the central tab (Fig. 10-47), has the punch and die adjusted to compensate for a springback, since the bend angle is quite liberal and coining was not possible. To solve the problem, using a deeper forming channel with a steeper angle of inclination and overbending the tab succeeded at producing the part to correct parameters. At the same time, the tip was bent at 90°, which, after the rest of the tab sprung back, became the *sharper-than-90°* angle needed. Of course, both the angle and the depth of the forming section had to be carefully assessed here, with dependence on the amount of springback thus obtained.

As the formed middle tab is sliding along with the strip movement, it needs a relief channel all the way to the end of the die to avoid obstacles that may otherwise hinder its progress. Such a relief channel also protects the bend from being flattened in the subsequent stations, due to the operation of the die.

In the next station, a section that constitutes the side shape of the bracket is blanked out of the strip. The shape of this punch and die was EDM-produced. The second half of the part's side shape is blanked out afterward.

Forming of two small tabs is performed in the next station, where the part is already attached to the strip by small bridges only. In the final station, the part is cut off the remainder of the strip, the two halves of the bracket are folded together, and the finished product is ejected from the die.

D2 punches and dies were used in this die, with carbide inserts in the forming section, to insure quality of products during long runs and to lessen the need for sharpening. Yet, the 0.030 in. [0.75 mm] thick stainless steel material did not behave its best, as it kept on

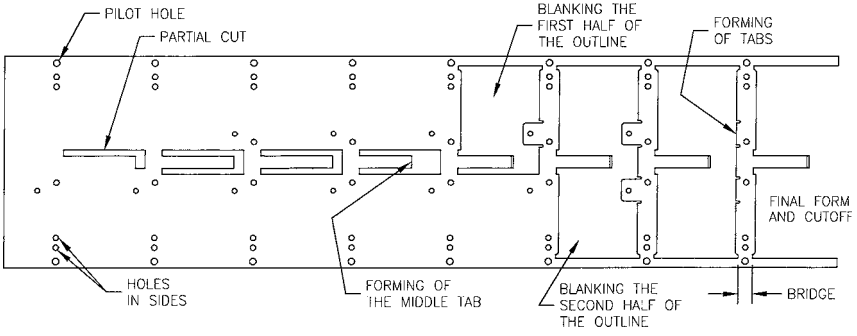

FIGURE 10-46 Die strip of the contact bracket. Holes and cuts are typical for both sides of the strip. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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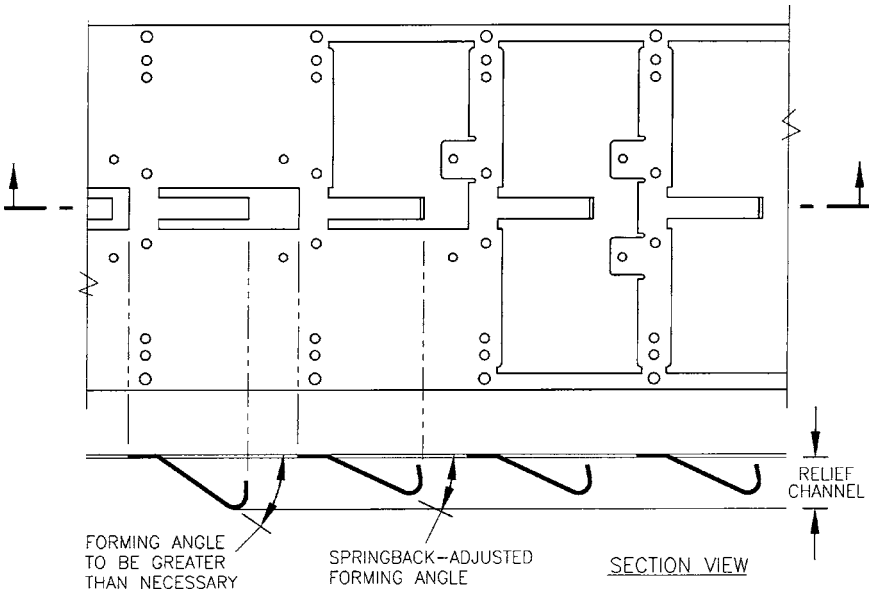

FIGURE 10-47 Detail of the tab-forming section. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

galling. Even where a tiny little section succumbed to galling, it immediately jammed the whole die. Ultimately, this problem was solved by usage of different lubricants.

10-3-5 U-Bracket

This part presents an interesting problem: not only the width of the tip is the same as the rear cutout; it is also made of a heavy gauge material, not allowing for a thin body punch to cut it out of the strip (see Fig. 10-48). If common parting methods were to be applied to this strip, the waste of material will be great whether the part will be fed horizontally or vertically. For these reasons, the designer decided to nest the tip of the first part within the cutout of the next (see Fig. 10-49).

The part is being produced from the strip of the same width as the blank in flat. At the beginning, a double-sided radius tool produces a relief slot with rounded outer edges. All openings are pierced afterward.

In the final station, the middle section of the bracket is retained by a spring stripper, while the sides are bent down. Right at that time, the blanking punch separates the tip of the second bracket from the body of the first. The first part is later pushed ahead by the movement of the strip, until it reaches the edge of the block, at which moment it either slides or drops down. The movement of the cutoff punch does not have to be excessive, so that no bending of the bracket's tip occurs. A material thickness-penetration and even slightly less will succeed at severing the bracket from the strip (see Fig. 10-50).

10-3-6 Bracket with Spring-Tensed Sides

Material thickness of this part is 0.078 in. [1.98 mm], which is a rather heavy gauge. The cutouts are produced earlier in the die and the bending begins with the two small tabs and the first bend of spring-acting side section. Keyed forming blocks are used in heavier materials

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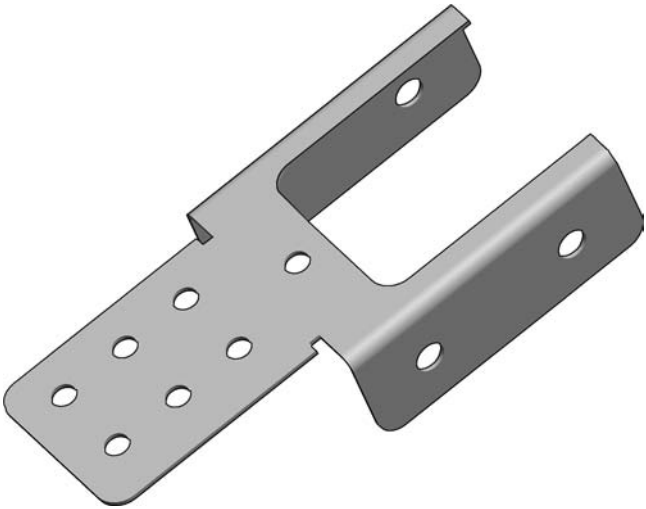

FIGURE 10-48 U-bracket. (*Reprinted with permission from Roselle Tool and Die, Roselle Park, NJ.*)

over 0.070 in. [1.75 mm]. Of advantage is that a single pressure pad can be used to wipe the small tabs up, while retaining the surface for forming of the outer sides down and immediately 45° up (see Fig. 10-51). The angle of thus formed side bends corresponds with that needed for the final shape. The bend radius of the side bend is quite small, but an adequate increase in the tool's body width is provided by a generous 45° bend angle.

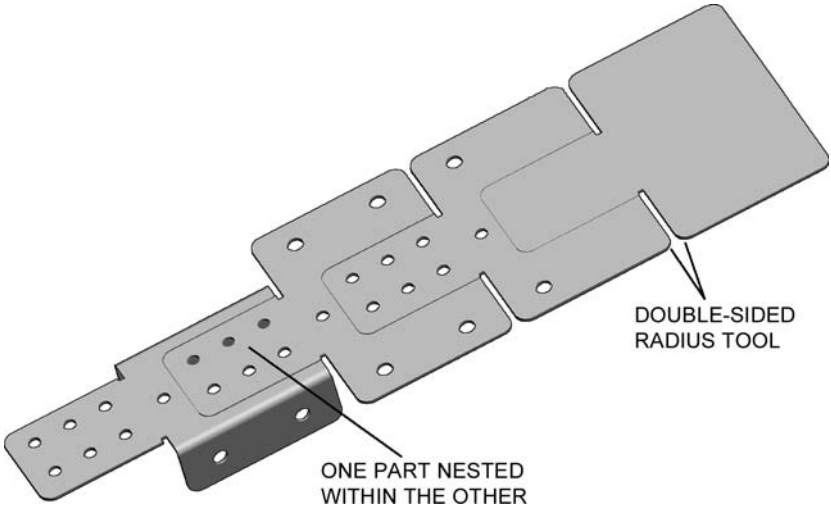

FIGURE 10-49 Die strip of the U-bracket. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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PRACTICAL DIE DESIGN

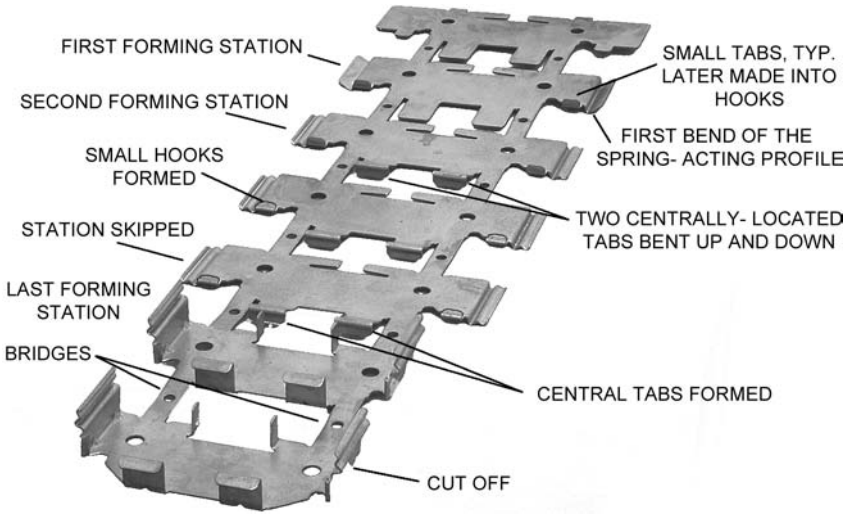

FIGURE 10-50 Strip of a bracket with spring-tensed sides. Both sides of the strip are identical. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

It is advantageous that all bending is the same on both sides of the strip, which keeps the part centered in the die. If bending were restricted to one side only, it will pull on the strip, relocating it toward the bent up side.

In the second forming station, the spring-acting shapes on each side are finalized, while two centrally located tabs are formed up (a rather shallow bend) and immediately, their ends are wiped down. These two central tabs are now exceeding the surface of the strip

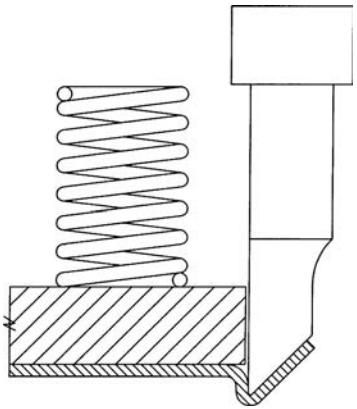

FIGURE 10-51 First forming punch. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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similarly as the two spring-acting side bends, one on each side, for which reason all subsequent punches and punch blocks must be designed in such a way as to not interfere with the progressing strip.

In the next station, the small side tabs are flattened to produce hooks for hanging and skipping the following station, the strip arrives at yet another forming station. Here the sides of the bracket with spring-acting ends are formed up and two stiffening ribs per each bend are produced at the same time. Two small central tabs are finish-formed, a stiffening rib per each bend being added as well. When designing this forming tool, a care must be taken not to interfere with the other two central tabs, already preformed in the previous station.

Finally, in the last station, cutoff of the bridges, which were used for connecting the parts together and for piloting of the strip through the die, is performed. The finished part is ejected from the die.

10-3-7 Stopper Bracket

The strip is shown bottom side up, which is opposite from its positioning in the die, where a majority of all bending is performed downward (see Fig. 10-52).

Pilot holes and the cuts in both sides of the strip are provided first. These cuts may be used for additional positioning if needed, with dependence on the behavior of the material during the subsequent forming and cutting. Even where not used for such a purpose, these first two cuts constitute the actual sides of the stopper bracket and will be formed up in the last station (see Fig. 10-53 for finished part).

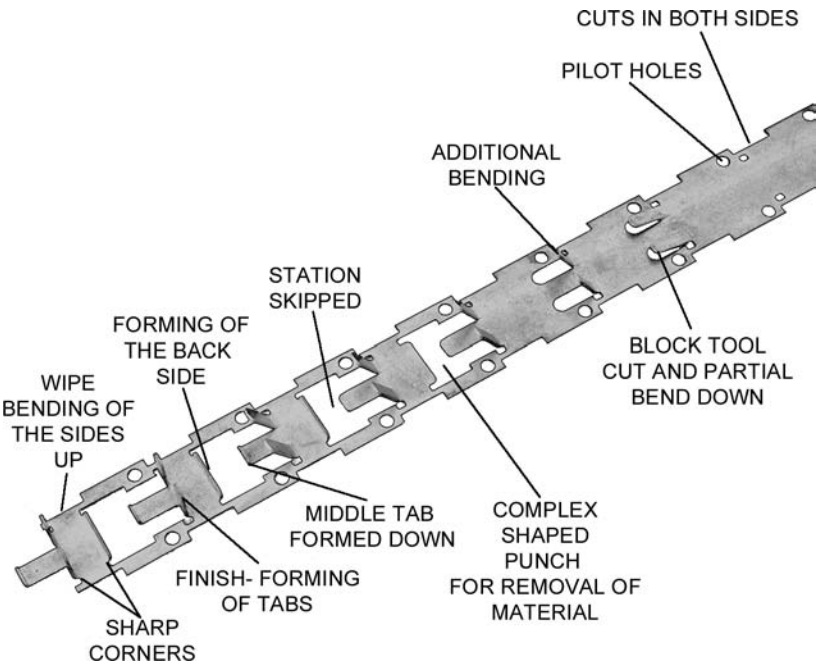
CUTS IN BOTH SIDES
PILOT HOLES
ADDITIONAL BENDING
STATION SKIPPED
FORMING OF THE BACK SIDE
WIPE BENDING OF THE SIDES UP
BLOCK TOOL CUT AND PARTIAL BEND DOWN
MIDDLE TAB FORMED DOWN
COMPLEX SHAPED PUNCH FOR REMOVAL OF MATERIAL
FINISH- FORMING OF TABS
SHARP CORNERS

FIGURE 10-52 Die strip of the stopper bracket. (*Reprinted with permission from Cowles Stamping Inc., New Haven, CT. Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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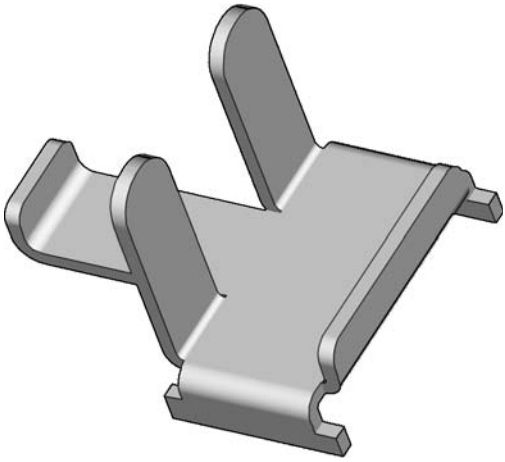

FIGURE 10-53 Stopper bracket, a finished part. (*Reprinted with permission from Cowles Stamping Inc., New Haven, CT.*)

The two rounded, centrally located tabs are knife-cut with a block tool, which at the same time bends them down. It is a lance form with no clearance between the tabs and the surrounding material. The bend is very shallow and it provides for the depth of cutting operation only, so that the punch can move down far enough to sever the material.

In the following station, the two tabs are bent down a bit more, just enough to clear the path of the punch which is removing the material around the middle tab and the back of the previous part. Because of the size of this punch, no additional operations could be performed in the previous station, nor in that which follows. Partial bending of the two tabs also produces somewhat shorter shape, which subsequently diminishes the depth of the relief channel in the die.

In the next station, the end of the middle tip is formed down, along with the backside of the part, and the two centrally located tabs are final-formed afterward. The last station provides for forming of the sides up, which is preceded by a cutoff of the part from the strip. The results of this operation must be carefully guarded, since the height of the two side bends and that of the backside of the part are quite small for the material thickness used. Additionally, the sharp corners of relief cuts may enhance the part's disposition toward cracking if too harsh bending process should be employed (see Fig. 10-53).

10-3-8 Mounting Shelf-Bracket

The mounting shelf-bracket presents an interesting task of forming two edges of a part, where most of the material between the two bends is removed. Observe the large rectangular cutout on the upper portion of the shelf (see Fig. 10-54). If produced prior to bending, distortions will surely result, as there is not enough material left to retain that section under a pressure pad. And bending first with cutting afterward will cause an interference of the cutting tools with the offset tab (see Fig. 10-55).

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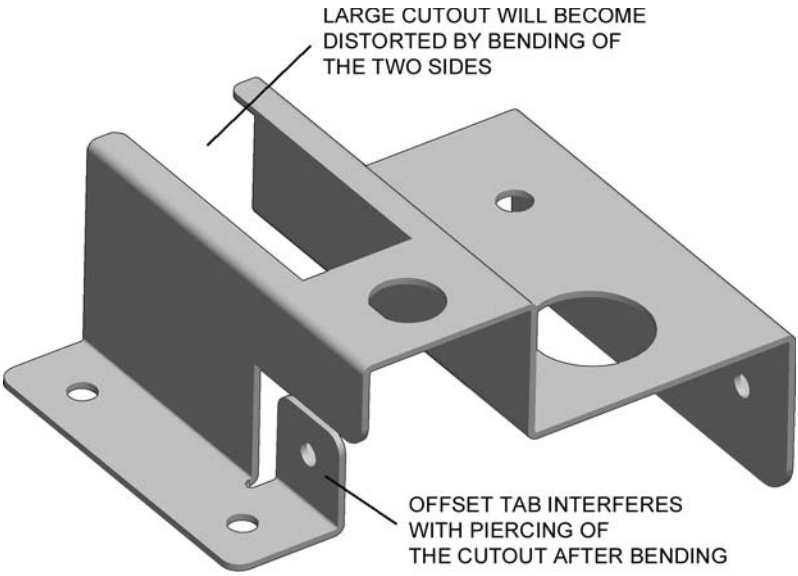

FIGURE 10-54 Mounting shelf-bracket. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

Another alternative, bending first, cutting afterward, and producing the offset tab as the last of the sequence of operations will demand a cam movement, which is an expensive add-on, often unacceptable.

The designer solved the problem differently (Fig. 10-56). In the first station, a partial area of the rectangular cutout was removed. This is the portion which is exactly over the

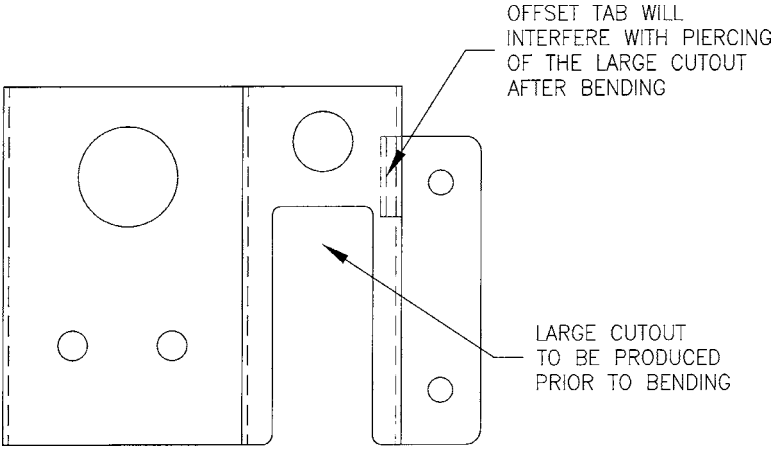

FIGURE 10-55 Interference of the tab with the cutting tool—Top view of the part. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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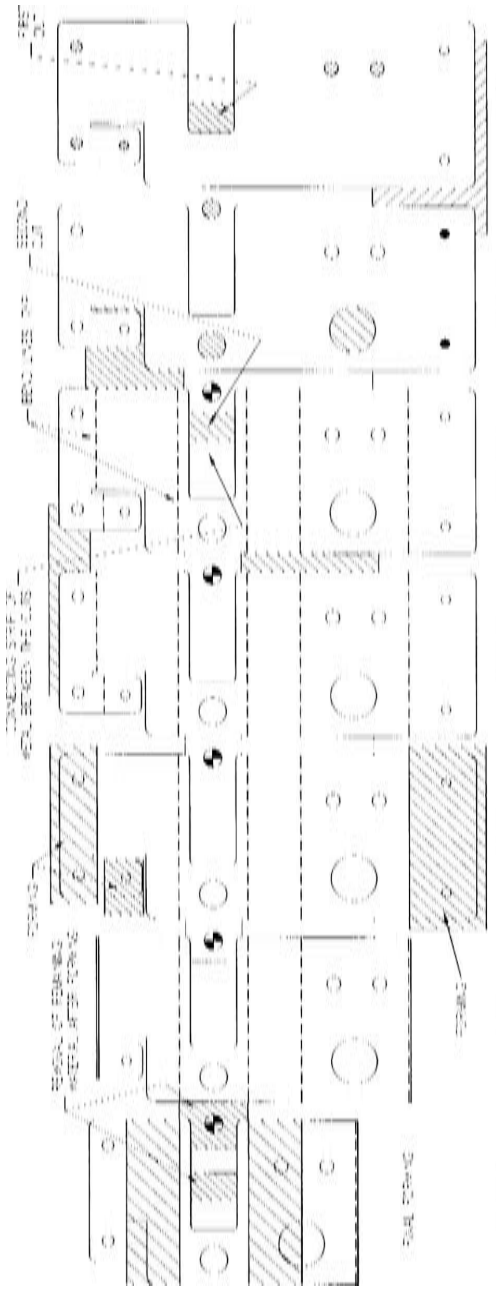

FIGURE 10-56 Die strip of the mounting shelf-bracket. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

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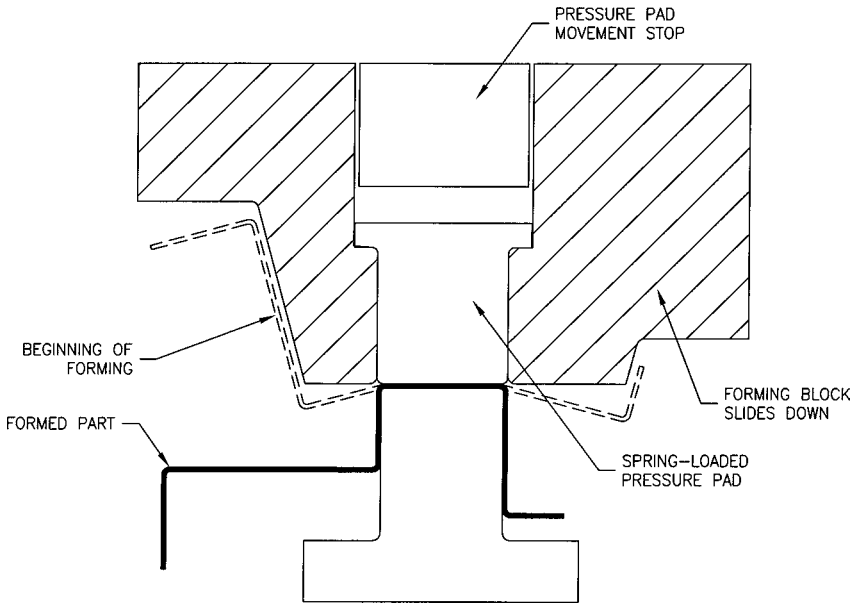

FIGURE 10-57 Forming section. (*Die design by George Kaminski of Roselle Tool and Die, Roselle Park, New Jersey. Reprinted with permission.*)

offset tab. The second cut, presented in station no. 3, was used to remove additional material, while leaving a connecting strip—a sort of a bridge of metal in between. The part was formed in the last station with cutoff of the joining strip performed as soon as bending was finished. Without such bridge holding the two sides to be formed, the forming could not be achieved by any other means. The detail of the forming punch and die is shown in Fig. 10-57.

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CHAPTER 11
DIE PROCESS QUALITY AND AUTOMATION, DIE MAINTENANCE

11-1 DIE PROTECTION AND THE CONTROL OF STAMPING PROCESS

A responsible and knowledgeable control of the die production process and subsequent die safety are of vital importance to the metal stamping production. With inadequate measures taken for the die safety, such may affect the functionality of the die and that of the press equipment in the most negative way. Metal stamping dies are very expensive devices, their design and manufacture being complex and demanding. Such tools must be protected from breakage or malfunction by all means, especially since their failure may bring about the deterioration and perhaps even destruction of the presses in which they are running.

For years now, safety of dies was controlled by limit switches, which are small devices, positioned in such a way as to detect any misfeed situations, buckling of material, or other failures of the die production process. Limit switches may be used as safety stops, feed-control devices, or as a means of any additional control of the die function.

However, the continuous demand for quality production at zero percentage of rejects and with a minimum amount of human intervention gave rise to widespread use of electronic sensors. Only electronic sensors wired to a *programmable logic controller* (PLC) are capable of stopping the press short of double punching, or where a foreign object appears on the surface of the strip or that of the die. Sensors can detect misalignment, wrong positioning, wrong distance, a lack of an assembly component, or faulty ejection of the part. Only with sensors, feeding the data to the PLC and taking immediate commands in return, can one operator run more than one press, overseeing but the delivery of material and attending sensor-induced press stoppages.

11-1-1 Limit Switches

Limit switches can also be called *mechanical switches*, as their function depends on the actual physical contact with the part or material, they are monitoring (Fig. 11-1*a*). These types of switches are widely used for detection of misfed sheet-metal strip, for indication of undesirable strip behavior, for control of scrap and parts' ejection, and for similar purposes.

In die production, where oil, lubricants, debris of material in combination with shop dirt are often abundant, the disadvantages of these devices are quite numerous. First of all, the need for their touching the object to locate it may sometimes give rise to a friction between

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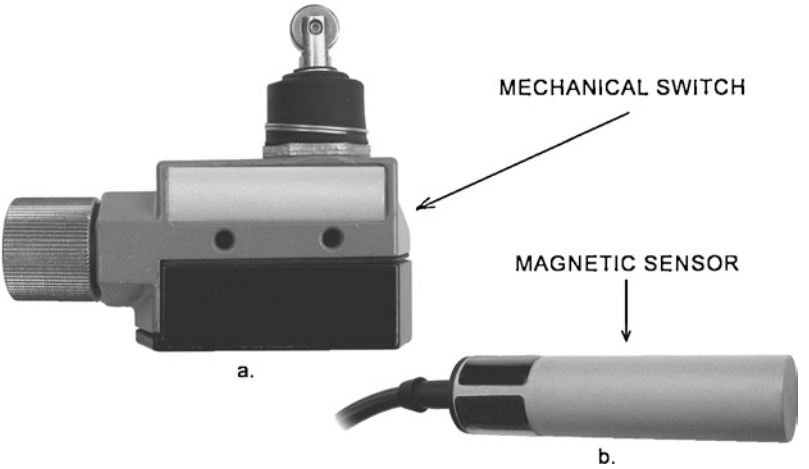

FIGURE 11-1 Control devices: *a.* Limit switch; *b*. Magnetic sensor.

the two. Scuffing, abrasion marks, wear, and damage to either component may be the result of such interaction. These types of switches are also quite bulky, with perhaps too many mechanical components that, over the time, may need an adjustment as they suffer from the effect of continuous vibrations produced by the press operation. The response time of limit switches may not be adequate for most of today's high-speed machinery, which may often render their inclusion in the die useless.

A sample of a die using limit switches is included in Fig. 11-2. Here a silver strip is being fed crosswise over a gilded metal strip. During the operation, a tiny silver slug is inserted into a small cavity with each stroke of the press. There are four hinge pads in this

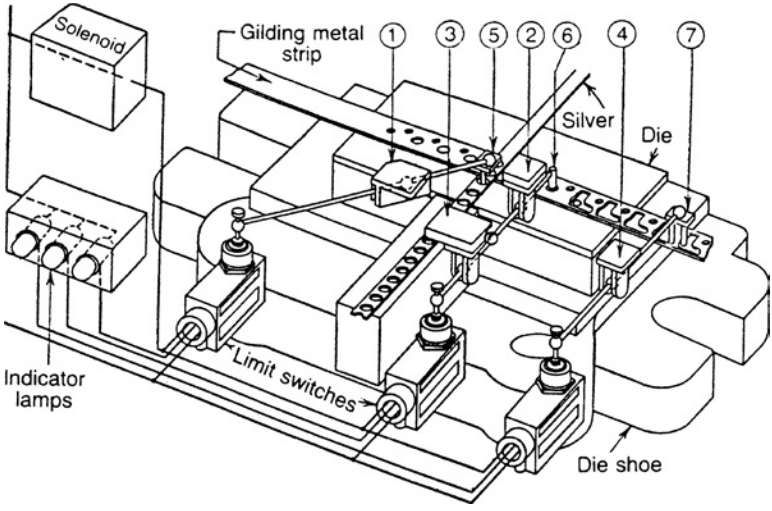

FIGURE 11-2 Limit switches guarding a progressive die. (*Reprinted with permission of the Society of Manufacturing Engineers, from the Die Design Handbook, Third Edition, copyright 1990.*)

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assembly (no. 1, 2, 3, and 4), which support the actuating levers. The pads are attached to the punch assembly, which is not included in the picture.

The two probes on the lever (item no. 5) enter the silver strip and control the expulsion of the silver slug; the probe no. 6 inspects the correctness of the slug's location within the gilded strip cavity. This probe's lever is flexed, so that the probe rests on the silver slug. If the slug would be missing, the probe would assume a somewhat lower position, which will trip the switch.

The two probes no. 7 control the advancement of the gilded metal material, as well as the removal of the blank from the strip. The whole assembly of probes and limit switches will stop the press where a misfeed or any other defective condition emerges.

In Fig. 11-3 is a limit switch used to check the advancing strip for misfeed. The lever (item no. 1) is held in tension by a spring, marked as item no. 2. The two limit switches, no. 3 and no. 4, are in contact with the arm of the switch. In the case of overfeed, the arm of the switch will put a pressure on the limit switch no. 4 and this in itself will stop the press. With too short a feed, the arm of the switch will lean in the other direction, which will also stop the press.

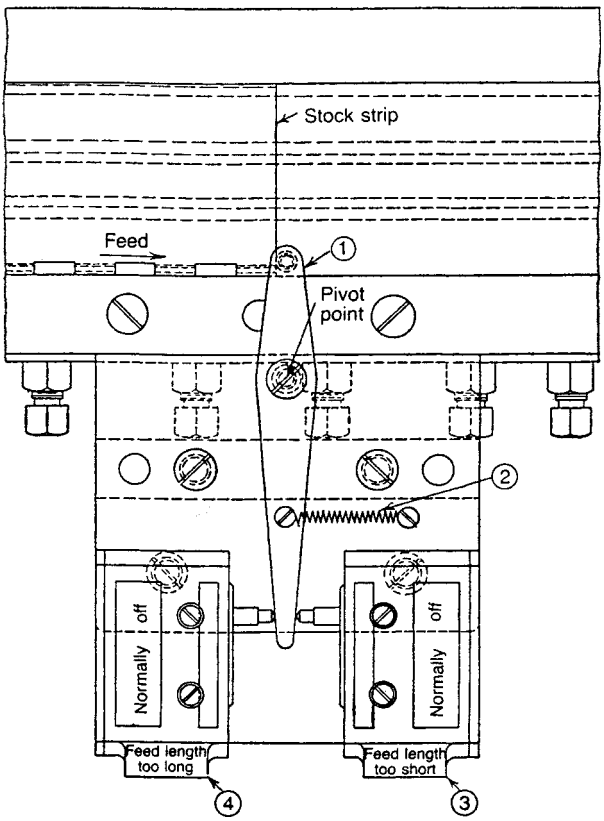

FIGURE 11-3 Use of limit switches to indicate misfeed of stock. (*Reprinted with permission of the Society of Manufacturing Engineers, from the Die Design Handbook, Third Edition, copyright 1990.*)

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11-1-2 Sensors

Since the mechanical contact devices suffer easily from the effect of metal stamping variables such as dirt, wear, oil, and possible damage to their mechanisms, over the years, noncontact sensors have been opted for. Inductive sensors operate on a passive-inductive principle of sending out a signal to another, remote, tool-mounted sensor, or to a group of sensors. The locally placed sensor, or a local head is connected to a PLC, which directs its function.

Using a solenoid coil, the local head generates a high-frequency electromagnetic field, which converts a DC supply voltage into an oscillating signal. The signal travels inductively across the air gap to the remote head, as shown in Fig. 11-4. On aligning of the remote head with the local head, the remote head is capable of converting the oscillating signal back into a DC voltage current. Both local and remote heads respond only to each other, which prevents any metallic debris from creating false inputs.

Amplifiers are used to control the sensor signals. One amplifier per head is usually all that is needed. These devices come in two forms, as PNP (sourcing) and NPN (sinking).

Sensors are capable of monitoring and controlling the die operation, while reporting the data thus collected to the PLC controller. Aside from inductive sensors, other detecting sensors come in several varieties, such as inductive or capacitive proximity sensors, ultrasonic sensors, magnetic, laser, photoelectric, and optical sensors.

Sensors are quite small in size, and due to a lack of mechanical components, they are immune to the vibrations of the press, as well as to the often-harsh metal stamping environment with all its oil, grease, lubricants, dirt, debris, and constant shock treatment. Their monitoring accuracy is quite high, and so is the repeatability of their function. Their housing usually comes in two types: shielded or unshielded. The unshielded models have greater sensing ranges than those that are shielded.

Sensors can detect many faults within the metal stamping environment. They can detect variation of feed progression along with faulty positioning of the strip or that of the parts. They can prevent double stamping, or stop the press when a slug is pulled. Sensors can monitor the ejection of parts, keep an eye on buckling or bowing of the strip, control the strip thickness and width. In conjunction with strain gauges, sensors can ascertain the level of pressure a part of a die is exposed to, can monitor the quality of forming operation, or provide a bend angle detection.

An additional application of sensors in metal stamping includes detection of tool breakage, detection of cam malfunction, control of burr size and its location, alignment of parts in assembly, control of spring-loaded components' function, and control of other specialized processes. The actual position of a sensor in the die is mandated by the analysis of potential problems that can arise during production. If the strip is expected to buckle, a sensor for detection of buckling should be implemented, and so on.

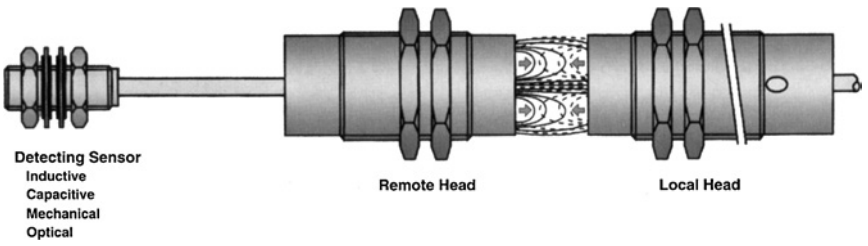

FIGURE 11-4 A local head converts DC supply voltage into an oscillating signal that travels inductively across an air gap to a remote head. (*From: Stamping Journal® May/June 2000, page 30, by Tom Rosenberg. Reprinted with permission from The Croydon Group, Ltd., Rockford, IL.*)

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Often, a small die needs but a limited amount of sensors, while a large, complex progressive die may need many more. There would most probably be no die that will need to have all its sections (or stations) monitored, for which reason problems within the die should be anticipated already in the designing stage and sensors be placed only in those areas.

This forces us to emphasize that there is no escape from the fact that the tooling along with the sensors must be designed at the same time. Where this is omitted, the die can often be found incapable of incorporating sensors or any other monitoring devices later on.

11-1-3 Vision Control

Vision control may be counted between the latest developments of the automatic control technology. It operates on a fairly simple basis of a camera, relentlessly surveying the area of its concern with an untiring eye. The camera records everything it sees, shooting back the values thus obtained into the controlling software for evaluation. When the camera stops seeing the picture it is trained to see, or when the picture is somewhat changed, it immediately sends out the signal, or stops the press, stops the production, or stops anything that it is programmed to stop (see Fig. 11-5).

Only because of the cameras' automatic control and continuous feedback, robots can grab the part or material always the same way and position them where they are programmed to. The robots are but following the data already input into their memory, while adjusting their validity per the variations observed by the camera. Where a part will be coming down the conveyor line in a different location than expected, the camera will pick up the differences and will send the information to the PLC, which in turn will instruct the robot to change the access data accordingly (Fig. 11-6). The whole process takes almost no time, and its accuracy and repeatability is incredible.

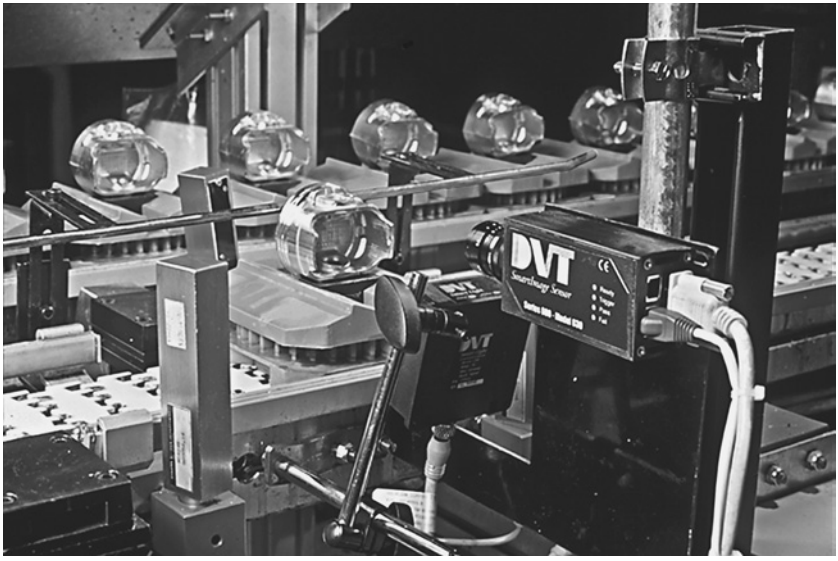

FIGURE 11-5 Camera observing the strip of advancing parts. (*Reprinted with permission from DVT Corporation, Norcross, GA.*)

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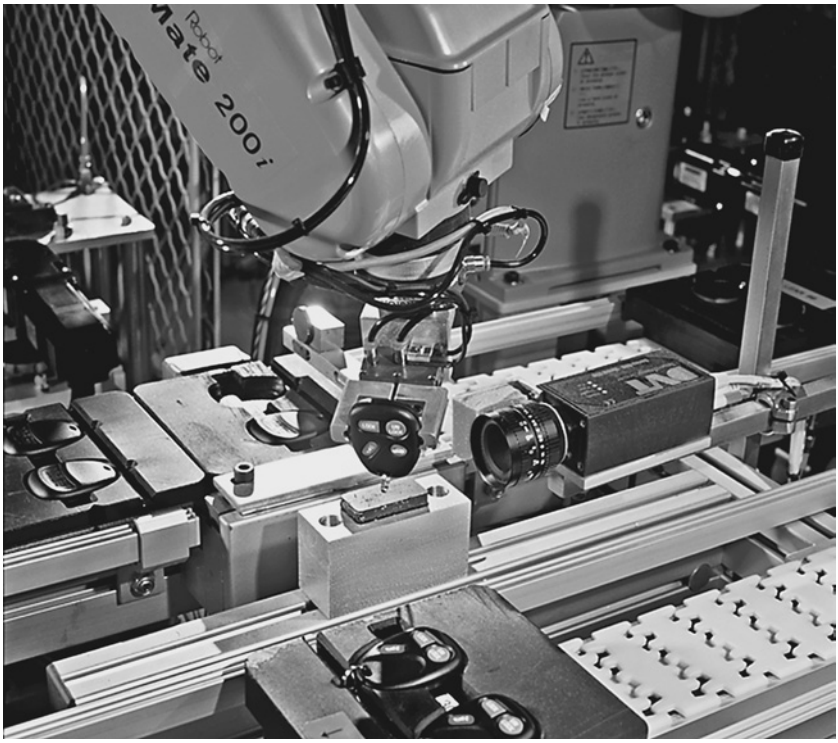

FIGURE 11-6 Camera observing a robotically-inserted component. (*Reprinted with permission from DVT Corporation, Norcross, GA.*)

The camera is capable of switching from one shape to another within a fraction of a second, and variations in size do not pose any problem either. Most probably, there is no fixture in the world that can locate the part more precisely and in a shorter amount of time than a properly programmed and properly controlled robot, guided by a vision system. For these reasons many fabricators may soon be seen as going away from the traditional fixturing as we know it, and may be turning for help to robotic controls.

By calibrating the system properly on installation and by training the camera's eye on the part which it has to handle, many such vision systems can operate faultlessly and tirelessly, day after day. Some cameras may be using detail-distinguishing features for closer observation. Other times, a surveillance of colors can be performed, or a check up for missing components of an assembly, alongside other applications.

Manufacturers of vision systems of quality control and production supervision claim the operator needs but a day of training to be able to use this type of equipment efficiently.

Yet, even this nearly-perfect control system suffers from one drawback: it is quite sensitive to light, or rather to a lack of it. Where poor lighting conditions exist, the camera may not "see" properly and mistakes may occur. Additionally, the vision system of stamping process control can be adversely affected by the pounding and vibrations of the press, for which reason the cameras must always be mounted aside from the press.

More description of the vision control approach of die monitoring is included further in Sec. 11-3.

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11-2 AUTOMATION AND IN-DIE PROCESSES

Blank or strip material for metal stamping can be fed into the dies by hand, or by a continuous strip feeding devices, or by robotics. More and more, manufacturers are leaning toward automatization of production, as it takes off the burden of factory personnel involvement, which, even though more versatile than machines, can suffer from fatigue due to monotonous tasks, which is when the human error emerges. Human error can cause irreparable damage to the tooling and machines, to the factory personnel themselves, and to everything else around.

Today, the tendency leans to involving people more in the design of the systems and equipment, more in the control of it, more in logistics of the work through the shop floor, than in actual manual production of parts.

True, there still are many shops where the operator grabs the precut sheet metal with tongs or sometimes with his bare hands, places it onto the die surface, and pressing the "on" buttons afterwards he or she bring about a stroke of the press. But such techniques are the thing of the past ages and the competitive, price-sensitive markets of present times do not tolerate the high cost of such production easily. Already shearing of the sheet metal to small, often precise-dimensioned pieces is quite expensive and running a die production using these blanks, aligning them in the die, watching carefully so that everything fits, hand-spraying the lubricant onto their surface, and activating the press controls, is a long-since antiqued dream. Or is it a nightmare?

11-2-1 In-Die Installation of Self-Clinching Fasteners

The installation of selfclinching fasteners was performed in such a way that a load of stamped part was brought to the assembly department, where the workers took the stampings, one by one, and adding the appropriate hardware to the location indicated on the print, they positioned these miniature pieces one after another with their bare and often work-roughened hands. Then they placed these mini assemblies into the specialized staking press, forcing the two parts together, one hit at a time.

Such an operation is not only slow and cumbersome; it is also prone to alignment variations; it endangers the equipment when the hardware is, by mistake, placed into the wrong opening. Many rejects can be produced this way, when due to the job fatigue originating in the repetitiveness of the performed task, the operator forgets to install some hardware. Over the years, various methods of counting the hardware components, of pictorial comparison control, of colored or see-through templates, were devised just to keep track of the type and amount of hardware to be assembled. Needless to say, there was not a great deal gained by any of these techniques.

Automatic bowl feeders were utilized later, but these too can feed only one type of hardware at a time and the rest of the components, if different, had to be added using a different press, a different setup, or a different assembly step, or even a different operator on a different day. In such a case, partially finished parts had to be set aside, carefully positioned onto pallets or into boxes. The high cost of stacking of the semifinished products, followed by removing them for subsequent installation of additional hardware components, and finally restacking them again for transport to the customer, speaks loudly against this procedure. Additionally, the original error, which is that of not including a component or two where they should be, prevails unaffected.

A better approach was taken when a standard PemSerter® was adapted to feed the hardware automatically into the specialized punch (Fig. 11-7) and assemble the hardware to the stampings already during the production of the die. The whole system is portable, as shown in Fig. 11-8, and can be moved from press to press, if necessary. It can be configured for

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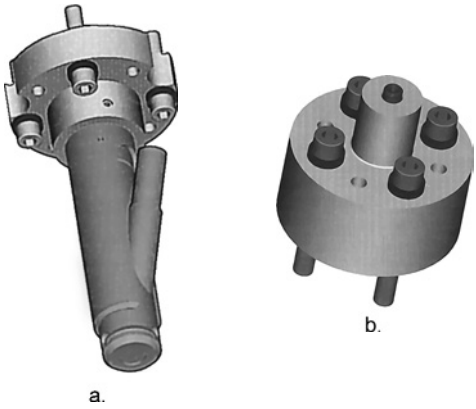

FIGURE 11-7 *a*. Hardware-inserting punch; *b*. Anvil. (*Reprinted with permission from PEM Fastening Systems, a PennEngineering Company, Danboro, Pennsylvania.*)

FIGURE 11-8 Automatic system of hardware insertion. (*Reprinted with permission from PEM Fastening Systems, a PennEngineering Company, Danboro, Pennsylvania.*)

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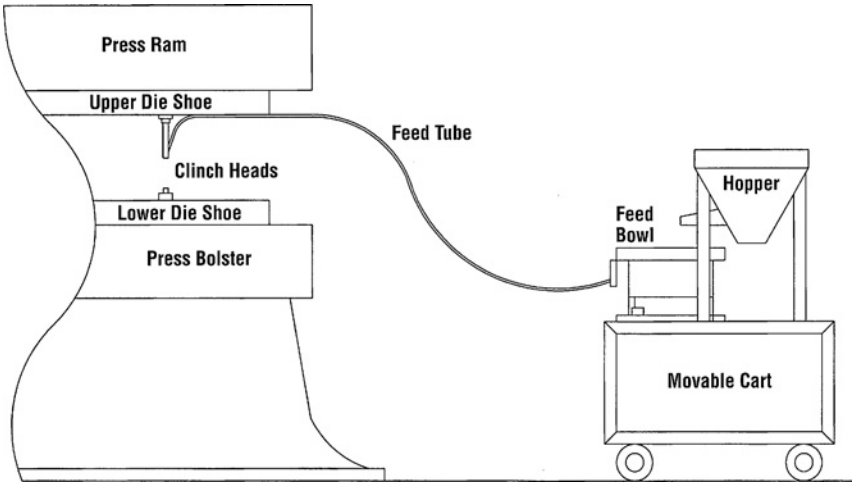

FIGURE 11-9 Schematics of the automatic hardware insertion. (*Reprinted with permission from PEM Fastening Systems, a PennEngineering Company, Danboro, Pennsylvania.*)

multiple hardware insertion and where the need for still more hardware arises, another wagon can be rolled to the production line. A feeding schematics is included in Fig. 11-9.

There are many variations to automatic hardware insertion. As shown previously in Fig. 11-6, a computer-driven robotic arm can be used to place the part into the die for hardware insertion. Computerized memory tells the robot exactly how to handle the part, as well as where to place it and when to do it. We all know, that there is no way the machine will ever forget or neglect this task, even at the end of a long and tiresome shift. Further synchronizing of the robotics with a press can be used with many other types and forms of fasteners.

11-2-2 In-Die Staking

Staking of any hardware is another such operation that could only benefit from automation. Manual staking, similarly to hardware insertion, is cumbersome and slow when done in a separate assembly operation. The inserted hardware is not always large enough for the operator's fingers to handle, and may often fall down, or be inserted the wrong way, and this way both the sheet-metal part and the hardware may end up in the scrap bin.

In-die staking utilizes a standard bowl feeding equipment as well, along with a customized transfer mechanism. The delivery of parts into the die is done via compressed air. A dual escapement bowl feeder can be used when placing two kinds of hardware at a time. The bowl feeder and its PLC controls are positioned on a portable cart, which allows for mobility from press to press. Designed for a quick change, standardized locators are utilized to attach the portable cart to the press, with quick disconnects for stud insertion and PLC controls.

To control the process and to monitor the quality of the parts, sensors are being used in the die, as shown in Fig. 11-10. The sensors monitor whether or not

- The material was properly fed
- The studs are present after staking
- The alignment of the studs is correct
- The part is properly ejected

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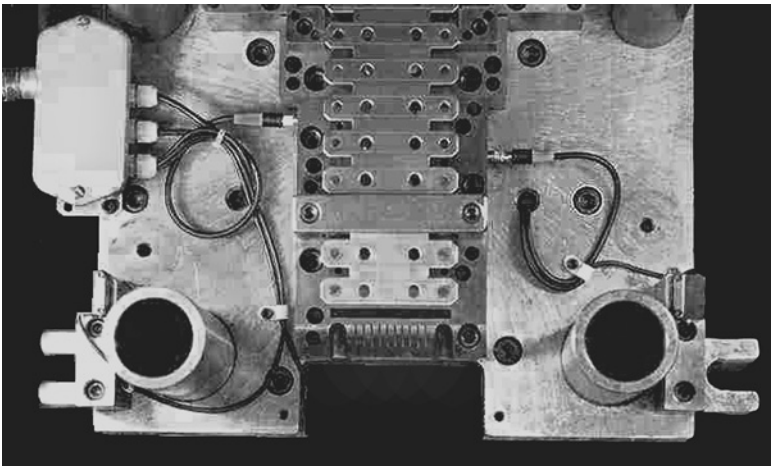

FIGURE 11-10 In-die staking: Sensors are monitoring the automatic placement of hardware. (*Reprinted with permission from GR Spring & Stamping, Grand Rapids, MI.*)

In this case, proximity sensors are implemented to detect the stud presence; photoelectric through beam sensors are there to verify the stock has fed properly. Another photoelectric sensor oversees the parts' ejection. And all sensors are integrated with the press controls, to prevent any problems during production.

11-2-3 In-Die Tapping

In-die tapping, not long ago considered impossible to achieve, is quickly becoming an industry standard (see Figs. 11-11 and 11-12). So far, the on-going research came up with three different types of tapping systems:

- Tapping with an external lead screw
- Tapping with an internal lead screw
- Tapping with a rack and pinion system

External lead screw systems use a series of gears, which are driven by a helix lead screw on descent of the press ram. The lead screw does not rotate; it only drives the gear assembly to generate and transfer the motion necessary for a tap cartridge to produce the thread. The length of the travel of the tap cartridge with respect to the ram travel is adjusted by changing the gear ratio. The gears are further adjustable to accommodate for a different thread pitch; they can tap downward or upward, vertically, horizontally, or under any angle.

A pitch multiplier allows for tapping of multiple holes in one operation, often varying the pitch from hole to hole. Where the press travel is too long, shock absorbers can be utilized to activate the tap cartridge only partially during the press stroke. For the opposite situation, where short press travel exists, a stroke reducer doubling the length of the tap path may be utilized.

Internal lead screw systems depend on a cam for transfer of the ram travel into tapping of openings to specified depths. Here the lead screw rotates when driven by the roller nut on its way down. The system can be designed as vertical or horizontal, with dependence on the preferences of the user.

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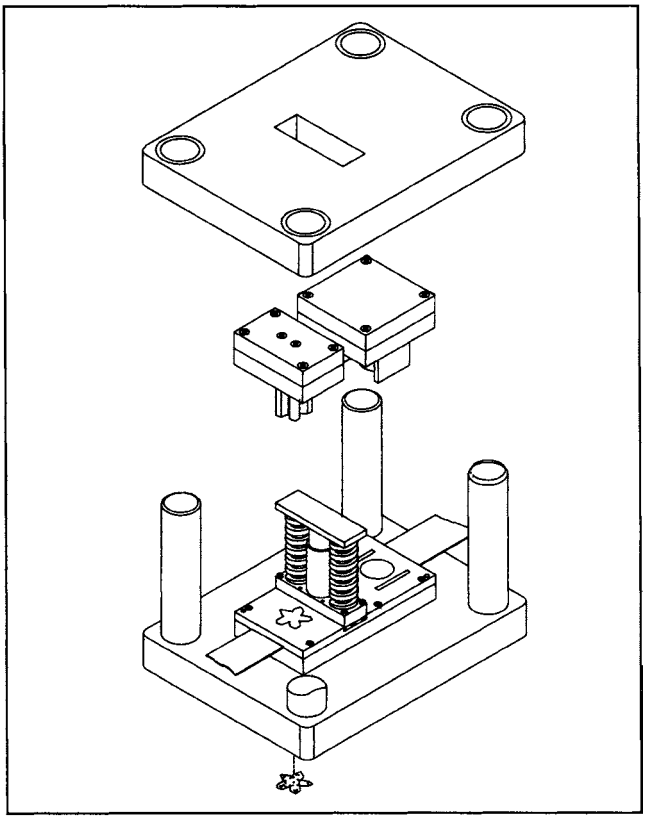
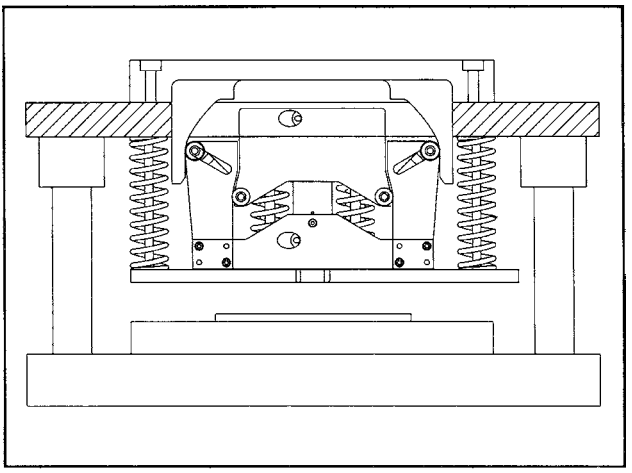


a.



b.

FIGURE 11-11 In-die tapping units: *a*. For a hydraulic press; *b*. For a mechanical press. (*Reprinted with permission from Danly IEM, Cleveland, OH.*)

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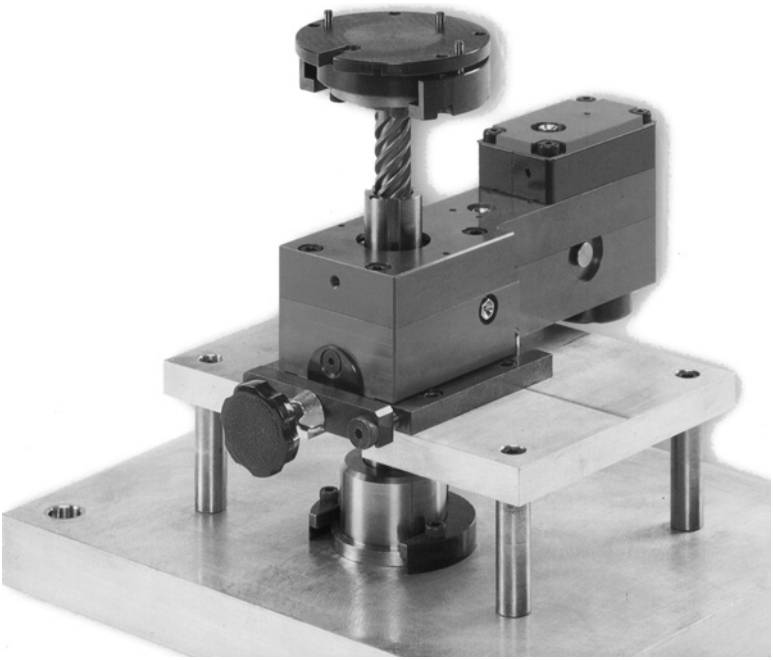

FIGURE 11-12 Self contained in-die tapping assembly. (*Reprinted with permission from Danly IEM, Cleveland, OH.*)

The lead screw and the roller nut are internally positioned because of precise mounting and gearing requirements. The lead screw rotates at high speeds, transferring its motion to the roll-forming tapping unit. Cams as a source of driving power have a definite advantage over gear assemblies, as their profiles can be developed in such a way that they bring the tapping unit to speed with no dependence on the ram acceleration. The change in pitch is possible too by swapping the tapping inserts.

Rack and pinion system of in-die tapping is similar to the external lead screw system, the difference being in a rack and pinion replacing the helical lead screw. Multiple tapping units can be attached with chain drives to the main drive system.

The design of a die that is expected to contain the tapping unit must consider this inclusion already in the first stages of planning. To retrofit existing dies will most often fare poorly, as the requirements for the inclusion will be difficult to meet. Already the fact that one rotation of the lead screw needs a sizeable portion of the ram's travel can disqualify many existing dies. The stripper's length of travel must be at least equal to the tapping stroke. Additionally, the height of the die must not accommodate only the tapping unit itself; it must further allow for an easy access for the purpose of lubricating and for the exchange of tapping inserts.

The tapping inserts produce the thread by roll-forming the material. Such a process generates a considerable amount of heat, for which reason the need for tapping fluid may be considerable. The size of the opening to be tapped must be per recommended diameter—here the designers should not forget that there are different diametral tap drill sizes recommended for a cut tap and for that which is roll-formed.

Naturally, for such an accuracy sensitive operation, the strip must be well guided through the die, with proper piloting at proper places. It is pertinent that at the engagement

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of the tapping unit, the opening to be tapped will be exactly where it should be and will not be swayed aside by strip buckling, defects in strip positioning, or other variables. A proper supervisory method of such in-die process via sensors is a must.

11-2-4 In-Die Welding

In-die resistance welding has lately achieved a large popularity. Years ago, nobody even dared to think about attaching a spot welder to the progressive die and produce welded assemblies right there, automatically. But then, we must realize that years ago, sensors were not as common as they are nowadays, and without sensors in-die welding may not be possible.

Sensors in the in-die welding process are necessary to ensure a total protection to the die. A thorough monitoring of parts' feed length, die components' position, scrap removal, and the overall die function as combined with the control of the moving strip, is essential. The welded-on objects must be monitored for their proper positioning within the die to make sure the welding electrode will engage the material right where it was planned and exactly the way it was planned.

The amount of pressure the upper electrode exerts toward the assembly-to-be-welded must be carefully monitored as well, and this information must be reported back to the PLC controller. This pressure is necessary not only to hold the parts in place, but to provide for a firm contact of the two, so that welding can occur (see Fig. 11-13). Without a positive contact of the components, a resistance weld is very difficult to produce. As can be easily imagined, oil, grease, or dirt on the surfaces may impair the weld quality.

Timing of the welding operation and that of the application of electric current should be developed and tested offline. A timing chart (see Fig. 11-14) shows the typical weld cycle's timing.

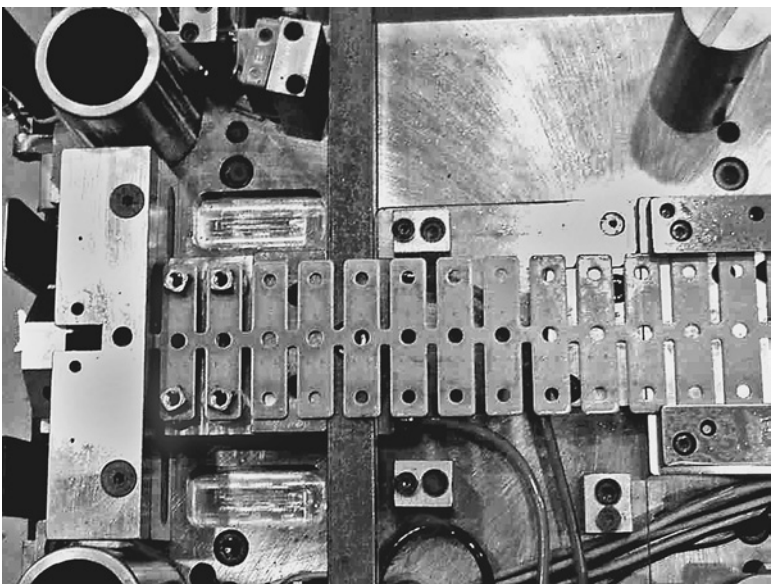

FIGURE 11-13 Welding of two nuts, in-die, top view. (*Reprinted with permission from GR Spring & Stamping, Grand Rapids, MI.*)

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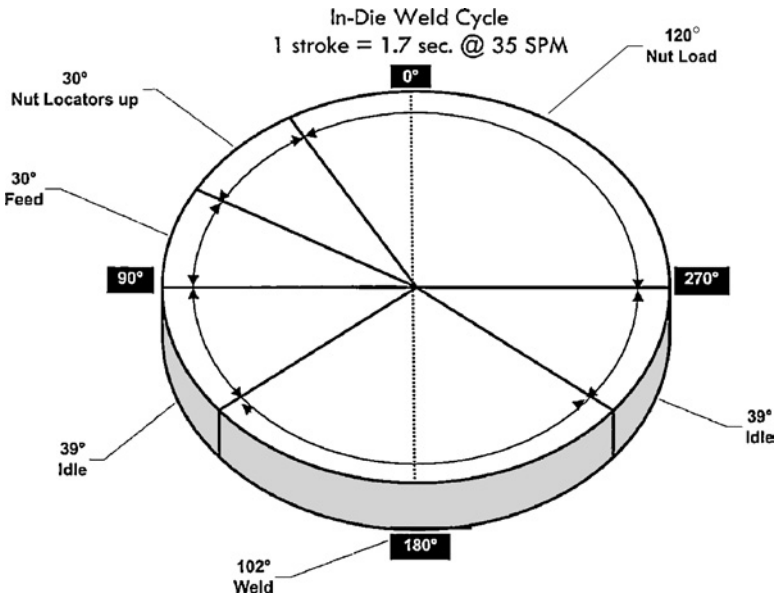

FIGURE 11-14 Timing of a resistance weld. (*Reprinted with permission from GR Spring & Stamping, Grand Rapids, MI.*)

The pressure of the welding unit must be constant, which is not all that easy when depending on the periodic movement of the ram of a mechanical press. Because of such type of an equipment, the amount of pressure reaches its greatest values near the bottom dead center and immediately drops down to zero in accordance with the ram's descend and ascend. To overcome this drawback, cams can be installed within the ram, and with the aid of linkage mechanism the press movement can be translated to suit the pressure distribution pattern needed for the welding head.

Resistance welding occurs easily when the two parts' surfaces are in close contact, pressed together. However, some parts are not quite flat, others are slightly twisted, and for these reasons, components to be attached by welding are sometimes provided with small projections to achieve a positive contact of the two. The projections are located on that side which will be in contact with the material, to which the other item will be welded. As can be seen in Fig. 1-55 previously, the first nut shown there has three welded projections on its bottom surface, whereas the second nut contains a round ridge, which is another way of providing a positive touch-contact with the substrate material.

In automatic in-die welding (see Figs. 11-15 and 11-16), sensors detecting a misfed item must be in place, as well as those that will monitor the electric current delivered to the

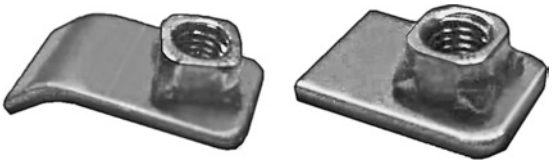

FIGURE 11-15 Samples of in-die welded nuts. (*Reprinted with permission from GR Spring & Stamping, Grand Rapids, MI.*)

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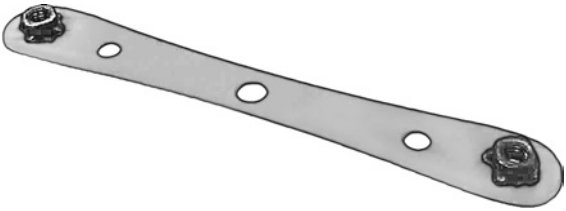

FIGURE 11-16 Sample of in-die welding. (*Reprinted with permission from GR Spring & Stamping, Grand Rapids, MI.*)

welder. Monitoring the amount of current that flows through the two materials during welding operation can be utilized as an in-die weld inspection. This can be automated to the point where the data reported by the sensors is compared to given parameters of acceptancy by the PLC controller, and on application of tolerance ranges, nonqualifying weldments will be disposed off into the scrap bin right on exiting the die.

Surprisingly, the actual welding time is very short, often measured in milliseconds, which should theoretically allow for a maximum of 600 welds per minute. This can be considered true only where the material of the strip and that of the component to be welded to it can be delivered into the die and properly positioned in such a short time (see Fig. 11-14).

The actual delivery of parts into the welding station can be achieved via vibratory bowl in the case of hardware. Where two sheet-metal parts are to be attached by welding, one of the strips can be fed under an angle, joining the second part right in the welding station. The exact placement and its monitoring is naturally of great importance.

The separation of welded assemblies from the strip can be achieved via either cutting the parts free, or via their breakage off the strip, or via any other method of choice. When breaking parts off the strip, minute amounts of material are being left in the corners for their attachment (see Fig. 11-17). This method is called *shake-and-break* in sheet-metal fabricating and the width of the joining strip is often dependent on testing. This is a similar method to that called *cut-and-carry* in diework, with the only difference being in the thickness of the web. Additionally, *cut-and-carry* parts have to be separated by a final blanking punch, whereas *shake-and-break* parts separate on shaking the strip or sheet, or on slightly hitting its surface. Of course, minute burrs may often be left where the metal bridges where positioned.

For in-die welding, a standalone cart can be utilized on which all the welding equipment is positioned (see Fig. 11-18). The cart can be rolled to any suitable press and the welding station implemented into the die. Of course, the die has to be designed with this inclusion in mind, as already mentioned with other in-die processes.

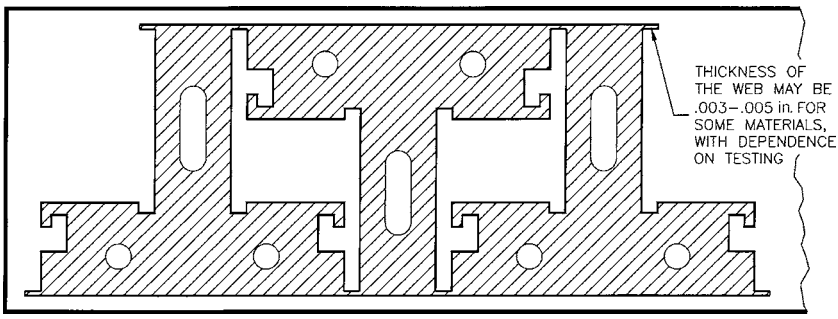

FIGURE 11-17 Shake-and-break method of parts' separation off the strip.

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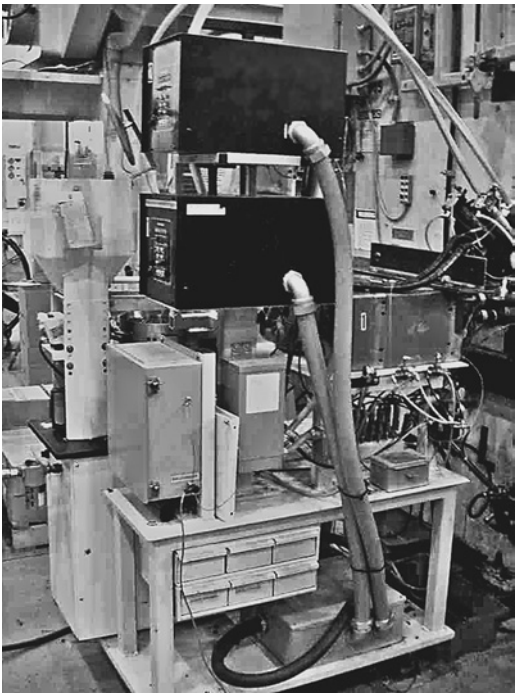

FIGURE 11-18 Cart with equipment for in-die resistance welding. (*Reprinted with permission from GR Spring & Stamping, Grand Rapids, MI.*)

11-2-5 Linear and Radial NC Multicenters

These unique machines were developed by Otto Bihler Maschinenfabrik, GmbH & Co, in Germany. They are complex assemblies of stations, either linearly or radially positioned around the machine board, which stands vertical (Figs. 11-19 and 11-20). Directed by the CAD/CAM software, with their components adjustable per the given task, the multicenters are capable of cutting and forming the components from either a single or multiple strips of material, assembling them together, attaching hardware, and welding where necessary.

As an example, a folded rectangular sleeve with a screw inserted through the joint surfaces (Fig. 11-21*a*) is produced in such a way that the part is cut from a strip and folded by an action of permanent cams. By *permanent* is meant that these cams are permanently included within the system, and can be adjusted to fit each new arrangement of components. The screw is fed through a tubing, it is inserted and tightened afterwards. The whole assembly may be ejected from the machine by sliding down a round rod, around which it is enwrapped.

A similar assembly shown in Fig. 11-21*b* is produced along the same lines, with the exception of another component, made in another die segment, using a different strip material, being added to the original part. Again, there is the cam action, the assembly, and the final fastener attached at the end.

An interlocking sleeve is produced from a single strip, retained by a centrally located bridge, formed closed, and cut off (see Fig. 11-22).

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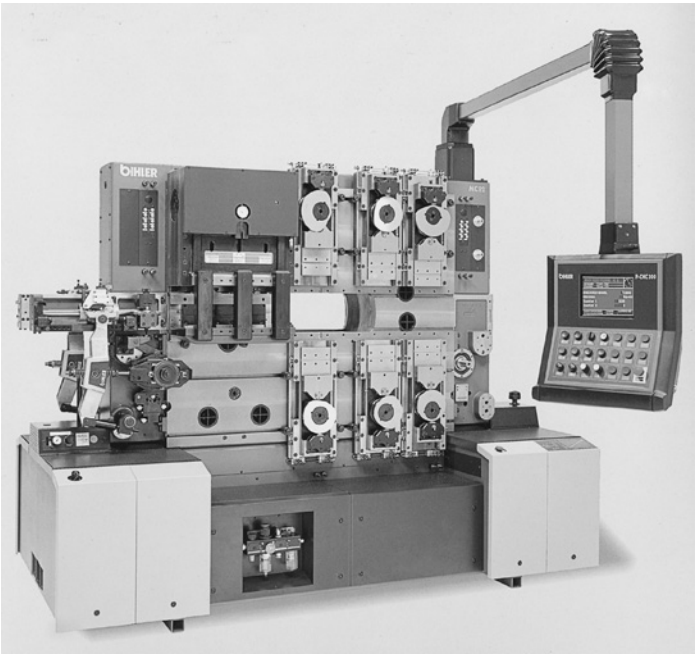

FIGURE 11-19 Linear NC multicenter. (*Reprinted with permission from Bihler of America, Inc., Alpha, NJ.*)

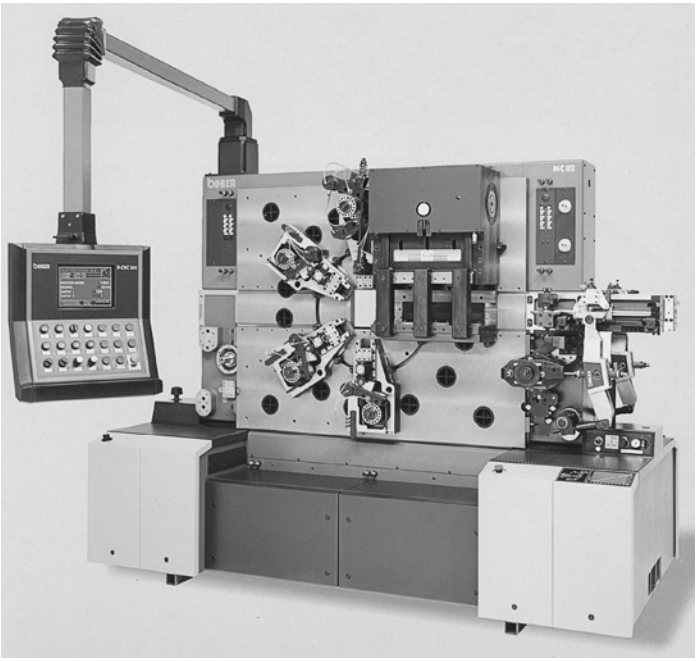

FIGURE 11-20 Radial NC multicenter. (*Reprinted with permission from Bihler of America, Inc., Alpha, NJ.*)

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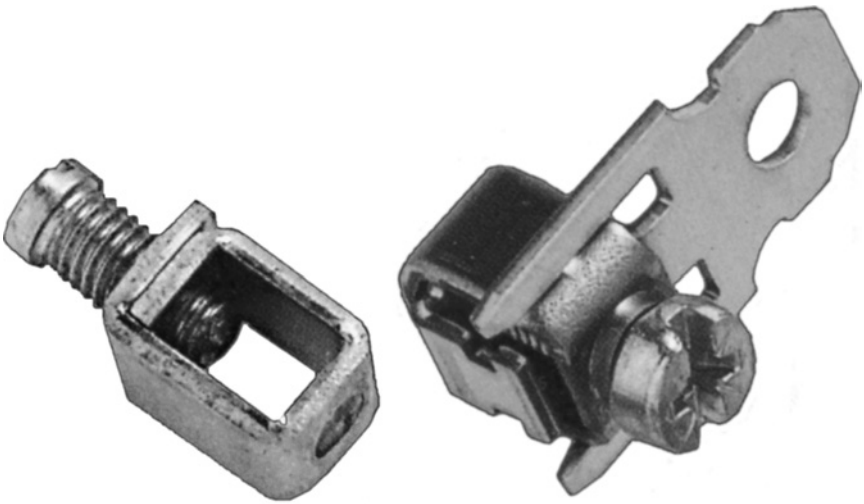

FIGURE 11-21 *a*. Folded rectangular sleeve; *b*. Assembly of several components. (*Reprinted with permission from Bihler of America, Inc., Alpha, NJ.*)

The principles of linear and radial approach behind these ideas are shown in Figs. 11-23 and 11-24.

11-2-6 Quick Die Change

With all the increased production demands of present times, the manufacturers not only depend on a quick assembly of all die components and enhancements and on a quick turnaround of the dies in the press, but, for that purpose, on a quick way to change the dies.

Hilma Co. came up with several products that can assist considerably with the quick die changing. First, when the die is delivered to the press, their die cart's upper surface consists of heavy duty roller bars, which ease the movement of heavy dies in and out of the press. Actually, a single operator can slide a bulky die in, effortlessly. Where needed, the press can be equipped with an out-sticking carrying consoles (either swiveling or fixed and supported), over which the die can be slid in and out. Again, the consoles are topped with rollers, over which the die slides.

The press bed, provided with hydraulically adjustable roller bars (Fig. 11-25*a*), makes moving of the heavy die easy to accomplish, especially where such is guided to its destination by additional side rollers. All clamping, changeover, and unclamping are monitored by inductive proximity switches, which are tied directly to the press controls.

Once the die is positioned, swing clamps can locate and hold the upper section of the tool to the press ram (Fig. 11-25*b*). The bottom shoe can be retained similarly, or by using hollow piston cylinder clamps (Fig. 11-25*c*), or similar clamping arrangement from their assortment of retaining devices. The clamps slide easily into the T-slot bolsters and rams, retracted by springs during the die switchover. This way, the whole procedure of die change takes minutes, where hours were spent previously on tightening nuts and bolts, aligning the die elements, die tryouts, and similar tasks. Figure 11-26 shows clamping technique for forming dies.

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FIGURE 11-22 Interlocking sleeve, die strip. (*Reprinted with permission from Bihler of America, Inc., Alpha, NJ.*)

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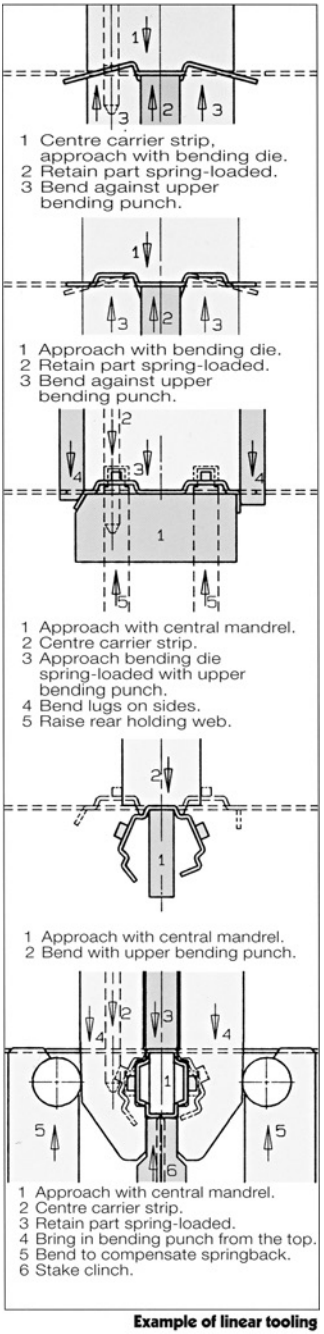
1 Centre carrier strip, approach with bending die.
2 Retain part spring-loaded.
3 Bend against upper bending punch.
1 Approach with bending die.
2 Retain part spring-loaded.
3 Bend against upper bending punch.
1 Approach with central mandrel.
2 Centre carrier strip.
3 Approach bending die spring-loaded with upper bending punch.
4 Bend lugs on sides.
5 Raise rear holding web.
1 Approach with central mandrel.
2 Bend with upper bending punch.
1 Approach with central mandrel.
2 Centre carrier strip.
3 Retain part spring-loaded.
4 Bring in bending punch from the top.
5 Bend to compensate springback.
6 Stake clinch.
Example of linear tooling

FIGURE 11-23 Principle of linear tooling. (*Reprinted with permission from Bihler of America, Inc., Alpha, NJ.*)

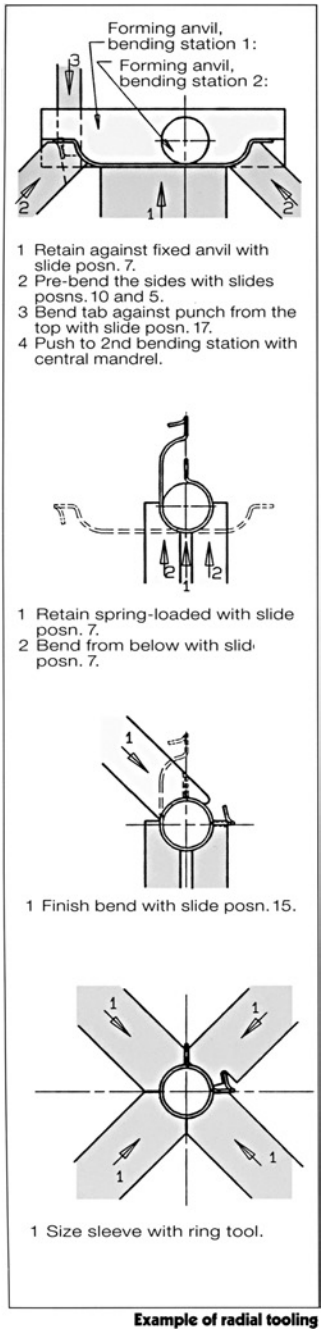
Forming anvil, bending station 1:
Forming anvil, bending station 2:
1 Retain against fixed anvil with slide posn. 7.
2 Pre-bend the sides with slides posns. 10 and 5.
3 Bend tab against punch from the top with slide posn. 17.
4 Push to 2nd bending station with central mandrel.
1 Retain spring-loaded with slide posn. 7.
2 Bend from below with slid posn. 7.
1 Finish bend with slide posn. 15.
1 Size sleeve with ring tool.
Example of radial tooling

FIGURE 11-24 Principle of radial tooling. (*Reprinted with permission from Bihler of America, Inc., Alpha, NJ.*)

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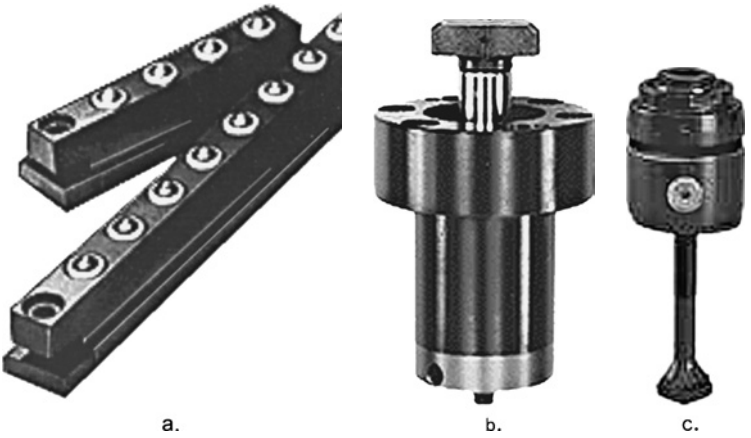

FIGURE 11-25 Quick die change: *a*. Roller bars; *b*. Double-acting Swing Sink Clamp; *c*. Hollow Piston. (*Reprinted with permission from Carr Lane Roemheld, Ellisville, MO.*)

11-3 AUTOMATED QUALITY CONTROL

Quality control can take many phases and many forms. Somewhere, there surely still exist corps of guys and gals that, equipped with calipers and micrometers, are routinely adding the values together on a scrap of greasy brown paper bag. Somewhere, there still are the workers that can calculate the sides of a triangle off the top of their heads and scribble long equations by which the future die will run on an oil-stained wrapping paper.

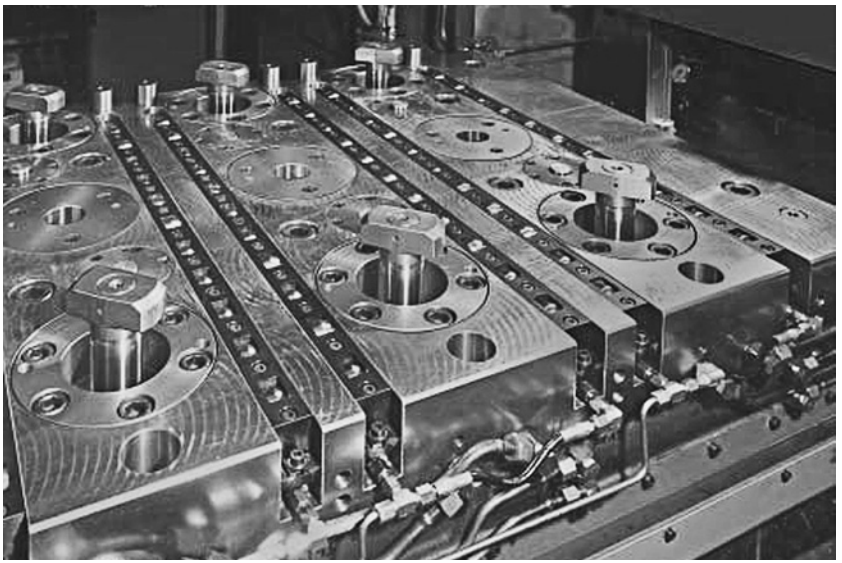

FIGURE 11-26 Clamping technique for forming dies. (*Reprinted with permission from Carr Lane Roemheld, Ellisville, MO.*)

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Many of them graduated into semiautomatic checking systems, where by positioning a probe they could derive the other dimensions off that location. The probe takes up the gap of the opening and the accuracy is quite impressive, yet the whole process may still be quite slow for today's manufacturing floor.

All these people are extremely valuable where spot-checking of the production is needed to make sure every tool and every machine is running correctly. But to do a first piece inspection this way, to measure every single opening, to observe if it fits within tolerance ranges of the print, while trying to ignore a score of workers waiting lined up behind their backs, which is an incredibly frustrating, expensive, and demanding process. It is also a waste of those people's talents.

An automatic, in-die measuring and quality control system is beginning to gain ground in metal stamping industry. Not that it is such a new method of control, but rather it was implemented everywhere else but in the metal stamping field. Only now, automated checking and testing, automated quality monitoring, and even automated quality improvements during the press run are being recognized as valid processes, worth implementing, and worth improving upon.

Every automated quality control system should be capable of collecting data obtained by the sensors, lasers, or other visually inspecting devices, and to process this information immediately, in order to feed the results back into the monitoring or controlling devices. True, some older PLC's may be too slow for today's high-speed presses and many failures may occur before the company leadership will stop blaming the shop personnel and will divert their attention to the responsiveness and a degree of obsoleteness of the equipment they are using.

A well-designed, automated quality control system should use the latest technology and be selected in replacement of old, inadequate arrangements. Such equipment must be capable of performing all the calculations needed to evaluate and arrange the data reported by sensors into meaningful bits of information. On the basis of these, the system should be able to distinguish a bad part from a good one, and send the bad part into a different storage bin for either further evaluation, or for scrap. The system should bear in memory the amount of rejects thus created and if, for example, too many bad parts are emerging from the same die station, a good system should display a warning for the operator and perhaps even shut the press down, if needed.

However, not all machines can be stopped at any time. Some may be tied to a whole conglomerate of feeding devices and stopping the process may wreak havoc between them. For this reason, a *shutdown protocol* has to be designed and be ready to be implemented should such a scenario occur. This protocol must determine which feeding device will be shut down first and which is to follow, which error messages should be displayed, and the final shut down of power, where needed.

The quality control system must further be capable of gathering all the data and displaying it either in a graph form, or as a statistical analysis for SPCs, if not other data interpretation. The amount of rejected parts should be accounted for as well, even if separate counters are to be installed at the production line.

A good start along these lines was achieved at the Georgia Tech laboratory, where their SmartImage Sensor Technology of high-performance vision system was developed and is now available for use in various industries. Their cameras are equipped with SmartImage sensors and with embedded PowerPC processors which display an optimum image stability and repeatability even in a high speed, high-resolution inspection environments. The system eliminates joysticks, frame grabbers, and CPU controllers and is relying only on the camera vision, which is trained to sense and report any variations from normal. The cameras are standalone units, small enough to fit one's palm, yet fully capable of delivering quality control inspection results, coordinating information for motion controllers, producing statistical process control data, plus 1D, 2D verification and reporting.

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As an additional equipment, a Smartlink unit, with a capability of accommodating up to 16 SmartImage sensors, can be utilized. The reporting of all cameras can be viewed from any monitor without the need for a computer. Images can be freezed on the screen for detailed inspection, and communication capabilities through standard Ethernet technology is common.

11-3-1 3D Laser Scanning and Reverse Engineering

Few years back, when the *coordinate measuring machines* (CMM) took over the quality control areas of manufacturing, they quickly became industry standard. It seemed that everyone had them and everyone used them. Unfortunately, already at that time, they were becoming obsolete. Perhaps they were developed a bit too late, perhaps the cost consciousness was spreading too fast, the machines were soon standing aside and many manufacturers were back to calipers and spot checking.

They reasoned, "after all, if I am using a precision-made die, or a numerically controlled equipment that's supposed to be accurate within ±.005 in. [0.13 mm], or ±.003 in. [0.08 mm], or whatever else, I don't need to check the outcome anymore." And hoping for the best, comparing the newly produced part to the previous product from the same tool against a lighted window, the production run was produced and delivered.

As a step between the next move forward, touch-dependent computerized applications emerged. With an arm, these could be guided to touch the actual 2D and later 3D parts, while the computer interpreted the data, calculated the results, and came up with the evaluation, printing all the forms, statistics, and other information.

Afterwards, a 3D laser scanning began. The advantage of having the part compared to the original 3D CAD file and the ease of the process quickly lured some pioneers into purchasing this equipment, in spite of the steep price tag it bore. When compared to CMM machines, laser scanners were found more precise, some boasting a ±.001 in. [0.025 mm] accuracy and some perhaps even less than that. Where a CMM 3D probe had to be guided over the complete surface of the scanned part slowly, step by step taking in the distances, the gaps, the valleys; laser scanning traverses in lines moving alongside the part. Since the laser ray is not touching the object which it is scanning, little particles of dirt do not hamper its function. This is not so with the CMM machines, which are literally thrown off balance by a spec of dirt or any other foreign matter on the part.

Another advantage of 3D laser scanning is the reverse engineering. This is a process, which allows for measuring of the actual product and transferring the data into a computer, where a 3D CAD model is built from thus gathered information. With the aid of reverse engineering, copies of actual objects can be produced in the computer's memory to be machined, or otherwise fabricated later in production.

Reverse engineering is used quite often where a manufacturer supplies his or her customer with a part submitted by another manufacturer. Often, these are *original equipment manufacturers* (OEMs), who are no longer interested in this or that production and yet the parts need to be made somehow. Automobile-serving industry is one of the major customers for this type of application.

11-3-2 Comparison of the Camera Vision and 3D Laser System of Quality Control

Some may ask which is a better tool for automated quality control in today's industrial environment. This is a great question, to which an answer is not easily obtainable. First of all, the area of application must be evaluated. Where the defects we are watching for are bright and outstanding, with relatively low levels of light needed to detect them, a camera is a better solution of the two. With darkened defects, needing a lot of light to be detected at all, or with defects extremely small in size, laser quality control systems should be preferred.

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Both, either very bright or very dark areas are easily viewable with a single laser scanner. Visibility of defects can be enhanced by the changes in its wavelength. Quality of detection (across the line) is consistent, regardless of the speed of the laser's line speed. Scanning can be done in ambient light, or using high power lighting.

On the other hand, the cost of laser scanning system is higher than that of the camera vision system. Lasers can also be found more expensive to run when using their scanning capabilities on predominantly bright fields. Their detecting capabilities for opaque, multicolored films is diminished as laser systems are color-blind; a white light is preferable with them.

Vision systems (i.e., cameras) are cheaper to buy and easier to install. Their functions are easy to learn as well, with problems surfacing only with aligning several cameras in a multicamera arrangement. However, since a single camera is usually not adequate, a multicamera system is most often a must.

Camera is sensitive to light coherency and for that reason it may need shrouding from the ambient light. Multicamera systems often cause problems because of the possibility of their alignment with the light source. This may cause inconsistencies from one camera to another and varying accuracy of detection may be experienced. These differences may increase with higher amounts of pixels.

Visual inspection may depend on a greater power consumption. Where upgrades are deemed necessary, new equipment should be resorted to, as upgrading optical equipment may not be found quite efficient.

11-3-3 Factors Affecting the Quality Control Procedures

In every metal stamping shop, as well as in any pressroom, there are many factors that can severely affect the quality of the parts and detection of errors. Not taking into consideration the so often quoted human error, there are still too many additional variables and influences. Already the presence of plasticizers in oil buildup on parts may impair the measurements' taking, among other things. Oil, dirt, debris, dust—these all may add to the possible errors and greatly affect the outcome of the inspection process.

Probably one of the most damaging influences on the outcome of quality control procedures is the effect of heat. The influence of heat on a metal part, so often ignored previously, is gaining ground with tighter and tighter tolerance ranges designers are specifying. Due to changes in temperature, a part with a tight tolerance may be within the specs at 70°F, while being totally out of spec at 90° or 100°F.

The control of temperature further presents the following dilemma: we may have the quality control room airconditioned and sanitized, which will keep the measuring tools at a constant temperature all day long. But when the workers from the shop bring in a large object and demand to have it inspected right away, how long does this object need to stay in the cooled room before it totally adapts to the controlled temperature? Or, can the warm-taken measurements be considered valid at all times?

The steel and almost every other material expands in heat and contracts with cold. After all, the average coefficient of thermal expansion is well known to us and its value being in the vicinity of almost one-thousandth inch/inch and 100°F (see Table 11-1) will certainly make a difference. A part 24 in. long will expand approximately .020 in. [0.50 mm] with every 100°F. With greater sizes and mass, the expansion due to heat naturally increases.

How do we then inspect a part, when gauges of all types, manual or electronic, automated or semi-automated, coordinate measuring machines, and all other measuring devices succumb to heat too and this way their reading has a built-in error already there?

With in-die measuring and quality inspection, care should be taken to ascertain where to measure and what to measure. There too, the temperature-caused error is present, especially in heat-producing operations. A part that becomes hot during metal stamping

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TABLE 11-1 Average Coefficient of Thermal Expansion of Selected Materials, at 68–212°F (in/in per °F)

Aluminum:		
	1100	13.2
	2011	12.7
	3003	12.9
	3004	13.3
	5000	13.2
	6061	13.1
	6151	12.9
	7075	13.1
Stainless Steel:		
	301	9.2
	302	9.2
	304	9.2
	316	9.2
	309	8.7
	310	8.0
	410	5.5
	416	5.5
	419	6.2
	420	5.5
Steel and its alloys:		6.5
Iron:		5.6
Zinc alloy		15.2

Note: Coefficient to be multiplied by 10^{-6}, e.g., $13.2 \times 10^{-6} = 0.0000132$.

process may be found out of spec and yet, on cooling down it is exactly per print. We should not forget though, that a rapid cooling or any aggressive thermal or handling changes may warp the part and it will never conform to the drawing's specification afterwards.

The temperature effect will also affect the tooling and its setup. After few hits, the punchings may be inspected and the die may be found slightly out of alignment. Shims are inserted here and there, and a new test is produced: still out of alignment. We shim again, we adjust, clean, and reinsert components, try the tool out and if we are not lucky, the tool may still be found out of alignment. Simply, nobody realized the ambient temperature was over 100°F and the material of the heat generating tooling, expanded in size.

11-4 DIE MAINTENANCE AND DIE ADJUSTMENTS

Die maintenance is a complex task. It involves many different operations, many different processes, and often it also involves the work of different people. Die maintenance starts from oiling the dies properly for production and storage. It continues with sharpening of

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punches and dies, with checking the springs for breakage, inspecting the blocks for wear and tear, checking the alignment of all die elements, inspecting cam return springs for misalignment or breakage, and even storing the first and the last part from the previous production run, for comparison.

Storing the last piece produced by the die can be very informative, for if someone may have taken the die off the shelf by mistake and if it fell off the forklift, next time the production starts and the die is found out of alignment or outright broken (with dependence on the height, of course), people would not be wondering what happened, what caused the problems, and will have a ready assumption for such a phenomenon.

Every well-designed die maintenance program needs proper documentation. Records of the die repair, notes on die alignment, these all should be kept methodically, accompanied by actual samples from that tool. When the die was down for adjustment, it should be recorded. When it was down for sharpening, it should be recorded. When it broke down for whatever reason, it must be on record as well.

These records of previous repairs and adjustments must not be limited to repairs only. Production records should be kept attached as well. Of interest is the amount of parts the die produced between the runs, between the repairs, and between the sharpenings. Quality control records should support this documentation by storing the results of each successive first-piece inspection. As already mentioned, die strikeouts should be stored as a means of recording the changes within the part, and their progression.

On the basis of these data, the toolmakers, engineers, and die designers would be able to evaluate each production run and see how many parts the die may produce before it needs any repairs, sharpenings, or adjustments. They should be able to ascertain which section of any die is giving them problems, and change the design of the next-in-line die in that area, while progressing toward a well-controlled data bank of information, which would be supported by a factory park of well-running dies. Such gathered data may become a gold mine of knowledge and experience, which is being put together for those who are interested and who are willing to heed its warnings, while speeding along with its recommendations.

11-4-1 Sharpening of Dies

Sharpening of dies is a tricky process. The more we sharpen them, the more we ruin them, and yet without sharpening, we may be ruining them still more. True, dies must be sharpened, but how much and how often that needs to be assessed and evaluated. A die with cutting punches made of cold-rolled steel at 35 HRc may need sharpening every two to three thousand pieces; but a die with carbide tooling should produce many, great many thousandths of parts more. Are we keeping track with our documentation considering the material the die was made from? Or, are we ignoring this subject altogether?

On the basis of previous records, we should be able to establish the frequency of sharpenings for a given sheet-metal material as well. Not all *low carbon cold-rolled strips* (LC CRS) come at 18 HRc or 28 HRc; the hardness of the material may vary greatly, if not specified on the order. Such variation in hardness will, of course, exert its influence on the tooling. Bending stations will produce different bends than those made during the last run; piercing tools may become dull sooner, or later, with dependence on the material hardness condition. The tolerance range variations of strip or sheet thickness should already be a common knowledge and as such, these should be monitored automatically.

On the basis of such information, we should be able to identify when (approximately, given the present orders) will the die need to be pulled off the press and sharpened.

But, how do we recognize the tool needs sharpening?

For that answer, we must look at the actual die strip—the strip that last entered the die and went through all the stations. With compound dies, it is the last product, or last few products that were made in that die. These samples always tell a story, should we watch

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closely to see it. Observe the cut lines—do they show excessive burrs? Are they displaying an inconsistency on a cross-section of the cut, or an inconsistency of the burr from one side of diameter to the other? Is the depth of the burnished area inconsistent with the die clearance we are using? If the answer to any of these questions is "yes," that die certainly needs sharpening.

We must also check for other changes in the part's surface or in its strip. We must look for nicks and scratches that may be due to a component's breakage. We must watch for disruptions of cutting lines, for changes in forming lines, for inadequacies in cutoffs. Problems may be hidden in a different pattern of ejection of parts or scrap, in a sudden appearance of sharp edges or small debris over the die surface, in impression of tooling or hardware in the part. These all signify either specific problems, components' breakage, or lack of alignment.

11-4-2 Detection of Problems

Early detection of possible problems is advisable. On the last part produced in the die, we may sometimes see a small hairline right by the edge. It seems to be caused by the forming operation, since it is quite close to the edge of the bend. On closer observation and comparison of blanks, we can see that the slight hairline was there already during the previous run and that each subsequent run it is more and more pronounced.

An experienced toolmaker's eye will immediately suspect a foul play, and indeed, on taking the die apart, a crack in the die block may be detected. This crack is not too bad, yet it seems to increase with every run of the tool.

Sharpening being suggested, it would not help much, but a good portion of the block may be found crumbling away under the grinding wheel. This in itself reveals the next chapter of the story: once, the die block cracked due to a tension produced by a poor alignment, and someone tried to repair the damage by welding. The weldments, being softer than the hardened tool steel block, gave in during the subsequent production runs and were slowly disintegrating under the production-related stress, and never addressed alignment-related stresses. Grinding but removed those portions of the weld that were already loose, and this way it bared the whole truth to those who were ready to see it.

Welding on a new section of the block may sometimes help, but other times it may produce more damage, with dependence on the professionality of the welder, aside from other aspects. Already the fact that it is very difficult to ascertain to which depth the previous weldments reach, is of no help. For this reason, the best bet is either to replace the whole block, or remove that portion which is found defective and install a brand-new section in its place. Welding is a tricky process when it comes to die repair. Often, whole segments are welded on in an attempt to repair this or that broken section. Welding of hardened blocks will certainly heat the surface next to the weld, producing different material qualities in that area. With dependence on the type of steel, the carbon may become displaced and a weak spot may be created this way. Such area when subjected to stress loading by the press function will display different properties than the surrounding surfaces. Whole sections may become unsupported, since a shallow gap or a recess may be formed this way. Bending sections may become misaligned and may be found breaking off in response to such discrepancies. Punches and dies may lose the firm support of hardened blocks and their excessive breakage may result.

Whenever something unexpected happens, like a whole section of the block is breaking off, or a more than normal wear and tear of some tooling can be observed, previous welding, now crumbling away, should be suspected and searched for.

Other times, we may find a small step in the part's formed surface. On investigation, faulty shimming of the forming block is discovered. Shimming can be quite insidious in that it will most often fill the gap as expected. But in production, over the time, the trapped

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air, oil, and perhaps even debris from in between the shims may be pushed out by the press work and the shims will settle down, revealing a step where previously was a flat surface.

Oftentimes, instead of shims, grinding the surface down to a flat and inserting a thin backup plate may be of greater help than sticking shims here and there, indiscriminately. Haphazardly placed shims will become uncontrollable and sooner or later nobody will know how many thousandths were added or removed, and where. One edge of the block may become shimmed +.025 in. [+0.64 mm] while the other edge may be down –0.005 in. [–0.13 mm] and the whole surface is out of flatness easily. A slant such as this will certainly incline the dies (or punches), producing misalignments in every section of it. With misalignments, we may sharpen the dies over and over without ever correcting the problem.

11-4-3 Prevention of Problems

For greater versatility and speed of exchange, all dies should be made of similar, if not common shut height. Every die should have a metal tag or another form of identification attached to its die block, indicating the tonnage and special setup procedures, along with other pertinent information. Some dies may look like heavy-duty tooling and yet, they may be producing only few cuts, which brings their tonnage down right there, and vice versa.

Press bed size with regard to the die size must be evaluated and perhaps the correct tonnage and correct bed size press assigned to each die in writing. Usually, as it is, someone at the company always "knows" which press the die goes to. But if this knowledgeable person takes a vacation or retires, a lot of damage can be incurred before the next one "to know" is trained.

With each incoming material, not only the thickness tolerance range of the batch should be scrutinized. Hardness of material must be inspected as well, since not all dies handle easily the differences of 10 HRc or more.

Where using compound dies with sheared blanks, control of blank sizes should be emphasized. If the in-house shear capacity is found inadequate, blanks should be purchased from elsewhere, cut to precise requirements. Where blanks are not used, coil-feeding system must be inspected and maintained along with the dies. What the die production depends on the most is a well-operating coil-feeding system.

11-4-4 Die Adjustments

Die adjustments may be necessary once in a while. But some dies may need more adjustments than the others. Where a complex die operation is involved, the results of each run, or the results of each sequence of parts does not have to be always the same. There may be dies, which, if adjusted manually, will have to be pulled off the press after every few hits.

For many of these special cases, automatic adjustment may be the solution. Such automated, in-die procedure combines several aspects of modern metal stamping. First of all, the parts are automatically inspected in the die, during production. The measurements thus obtained are reported to the controller, which is capable of evaluating the data and sending the commands resulting from such back into the die system.

As shown in Fig. 11-27, a die producing a curl on the part needs quite frequent adjustments of the lower die portion. For this purpose, a gradual slant was produced on the bottom die block surface, over which an adjusting screw can ride. The screw, driven by the stepping motor, can move in and out, which increases or decreases the height of the die block.

As soon as a discrepancy can be recognized by an in-die measuring device and reported to the PLC controller, the latter issues a signal to the stepping motor, which moves the adjusting screw in the direction indicated. This way, either the die block's surface is lowered, or pushed upward. The movement is gradual with no harsh effect on the die. The new

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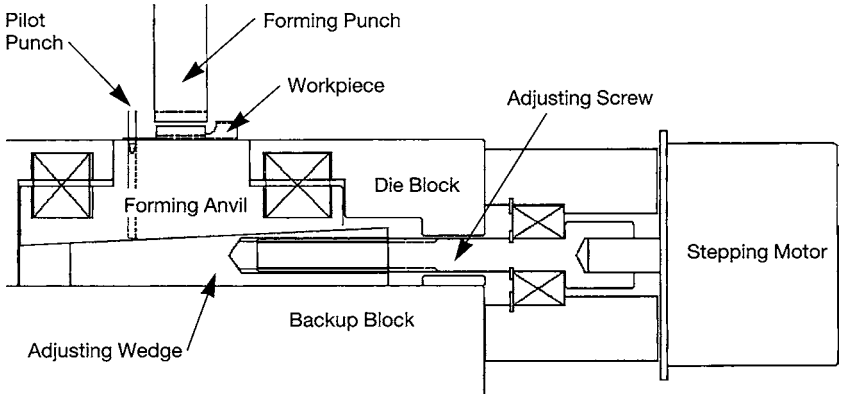

FIGURE 11-27 Sliding wedge adjustment. (*From: Metalforming Magazine® February 1999, pg. 35. Reprinted with permission from PMA Services, Inc., Independence, OH.*)

forming data being continuously read off the produced parts are always compared to the set values and their tolerance ranges by the controller, and the height of the die block adjusted up and down according to necessity.

Once recognized as possible, in-die adjustments may be used for a wide range of applications. For example, where five parts are to be produced exactly the same and the sixth part must have the central opening eliminated, an in-die adjustment that will decrease the height of this punch, so that it cannot reach the strip surface and produce a cut, can be used. Other cases may include an adjustment of a cam movement, bending section's height changes, forming angle variations. Or a press shut height adaptation for the precise control of the strip penetration.

The application of such technology is a wide-opened field. And combined with other advances in metal stamping areal, it makes the process of metal stamping production much more controllable and predictable than ever.

11-5 BEHAVIOR SIMULATING SOFTWARE

There are many software packages on the market nowadays. Some claim being able to start the die design from strip layout, progressing to the complex, full-blown 3D die arrangement, which may be true, usually at a cost. It is neither cheap nor fast and easy to design a die in 3D, and many times it is not even necessary. And to derive the strip from such a design or to start the 3D buildup from such a strip, is sometimes, even with the most respected software programs, quite a task.

On the other hand, to those who are used to 3D way of thinking and are well adapted to this method, a 3D designing software package may be the way to go. One should be careful though, whether or not is the software capable of working in a 2D environment as well, for some of them simply cannot, no matter what the sales rep claims. In the field of die design, as in many other design areas, the chance of occasionally working in 2D is always present. I am writing these words in spite of the fact that I myself am a great proponent and user of several 3D CAD programs.

With die design, the combination of 2D and 3D, and the versatility of switching from one to the other is very important. The strip layout cannot always be modeled out of a 3D computerized mass, already equipped with a thickness. Not every software allows for flattening

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of the image, or to import/export a 2D *dxf* or *dwg* files to form the basis of 3D models. Further, 3D models can be complex and sometimes outright clumsy. In some programs, each element of an assembly carries along a 3D planes' formation of its own and that of all its components and with ten or more parts of a die on the same screen, it is sometimes difficult to recognize the part itself for all the planes', axes', and point's description. If at least some of them could be switched off, but they cannot; a selective shutoff is not always provided for.

Some major software programs are capable of performing the *finite element analysis* (FEA), which is a fine tool where the stresses on the part or those on the die are of concern. The software can calculate the stress and strain applied to the part's or die's structure from either side, as needed. It can generate the simulation of failure and ascertain the amount of pressure, stress, or buckling needed to produce this event. With a dependence on the method of application and with a dependence on the software used, it can calculate the finest nuances of part's stress loading and show where the design could be improved on.

11-5-1 Folding and Unfolding Software, Blank Development

Forming of parts can often be a great dilemma to die designers and diemakers. There are just too many variables that can be threatening each such operation: the gap between the tooling, the speed of the die, responsiveness of the formed material, strain hardening, to name but a few. Fortunately, there are software packages with forming simulation capabilities, useful in the metal stamping field for the calculation of flat blanks and for the development of tooling. Such software can produce blank layouts of complex parts in but seconds and figure out the best arrangement on the strip on command.

A good forming software is capable of evaluating the thinning of metal in areas of concern, finding out where the material will stretch, predict deformation, buckling, and tearing, establish the amount of springback, or suggest the appropriate nesting for the most economical utilization of the strip material. Folding or flattening of models is often a routine task with them.

Some may use the software for blank development and die design, while others may use it for quoting purposes, for material formability assessment, or just to establish the number of stations needed in the die. The software can be further utilized for the design and analysis of tooling, and may already then, in the design stage, alert the user to the areas of concern. Feasibility studies can be performed along with design optimization.

11-5-2 Finite Element Analysis Software (FEA)

Perhaps some FEA may be considered outdated in that they take a complex problem of a moving piece of equipment and apply all the textbook conditions and textbook restrictions to it, without any regard for accuracy of data. Such analyses are strictly theoretical, with not much of a connection with the real world.

Other analyses take into account not only the stresses exerted upon the piece of equipment by the forces known; they further evaluate the unknown and undisclosed stresses produced by the environment, which that particular product or equipment is geared for. For example, evaluating the stresses upon a cellular phone that fell off the table takes into account the fall, the crash, and the destruction of the unit. This type of analysis is called a *simulation of an event*.

A FEA such as this, can ascertain not only the linear dynamics or structural analysis of an assembly of parts. It can further determine the thermal, electrostatic, mechanical, and other influences upon the single product, or the assembly of parts.

Generally speaking, the computers are here to help us design better parts and devise better manufacturing procedures. They are a great tool where properly used. Already the fact

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DIE PROCESS QUALITY AND AUTOMATION, DIE MAINTENANCE

that whole assemblies of parts can be copied from one adaptation to another and changed per new demands, or that standardized libraries of parts can be imported where needed, a 3D cross-sectional view can be created to illustrate components' placement in complex assemblies, speak for themselves.

Aside from these obvious benefits, a possibility of presenting a product that has not yet been made and showing its detailed features to an audience that, even though very capable, is not trained to see a real object, amidst the network of lines of a 2D drawing, is but another bonus coming to those who are willing to master such techniques. To know a future part so well that we are familiar even with its weak points and can improve them long before we build the first prototype, is worth a lot.

Along similar lines, an additional enhancement to the toolmaker's, tool designer's, or engineer's job is a simple digital camera. With the aid of such undemanding item, assembly procedures can be documented and stored in the computer, from where they can be pulled for reruns, or adapted for anything else.

The computerized world of today promises a great future. We just have to learn to utilize all these tools placed at our disposal, and we have to devise ways and means of profiting by it.

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CHAPTER 12
SPRINGS, THEIR DESIGN AND CALCULATIONS

12-1 SPRINGS AND THEIR PROPERTIES

Well-functioning springs are one of the most important prerequisites of a good die function. After all, what good is the drawing operation if the part cannot be stripped off the punch because there is not enough spring power behind the pressure pad? Or—what kind of parts will emerge from a die where the spring stripper is not spring-loaded adequately?

If ample pressure is the absolute basic of a good die operation, then springs are the most vital parts of every die.

12-1-1 Spring Materials

Springs are elements designed to withstand great amounts of deflection and return to their original shape and size on its release. To be capable of such cyclical loading, spring materials must possess very high elastic limits.

Often materials not specifically made for the spring application are utilized for that purpose because their elastic limits are within the above requirements. Steels of medium-carbon and high-carbon content are considered good spring materials. Where a copper-base alloy is required, beryllium copper and phosphor bronze are utilized.

The surface quality of the spring material has a considerable influence on the function of a spring, namely, on its strength and fatigue. Where possible, the surface finish has to be of the highest grade, preferably polished. This is especially important with closely wound springs, where friction between single coils may create minute defects in their surface, which subsequently will cause the spring to crack. Music wire, the highest-quality spring material, is polished, and its surface is almost defect-free.

Of course, the higher quality the material, the more expensive it is. The designer should strive to find the best combination of price versus quality for each particular job.

A brief description of basic spring materials is included in Table 12-1, which provides a rough comparison of properties, usefulness, and some specific aspects. (Additional properties of spring temper alloy steel are presented later in Table 12-8.)

12-1-1-1 High-Carbon Spring-Steel Wire. This group of spring materials is lowest in cost, which may account for its widespread use. It does not take impact loading or shock treatment well. Also it should not be used in extreme temperatures, high or low. Main representatives of this group are listed, with the percent of carbon (C) given.

Music wire, ASTM A228 (0.80 to 0.95 percent C). Good for high stresses caused by cyclic repeated loading. A high-tensile-strength material, available as (cadmium or tin) preplated.

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TABLE 12-1 Typical Properties of Common Spring Materials

Common name	Young's modulus E[a] MPa 10^3	Young's modulus E[a] lb/in^2 10^6	Modulus of rigidity G[a] MPa 10^3	Modulus of rigidity G[a] lb/in^2 10^6	Density[a] g/cm^3	Density[a] (lb/in^3)	Electrical conductivity,[a] % IACS	Sizes normally available[b] Min. mm	Min. (in)	Max. mm	Max. (in)	Typical surface quality[c]	Maximum service temperature[d] °C	°F
Carbon-steel wires:														
Music[e]	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.10	(0.004)	6.35	(0.250)	1	120	250
Hard drawn[e]	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.13	(0.005)	16	(0.625)	3	150	250
Oil tempered	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.50	(0.020)	16	(0.625)	3	150	300
Valve spring	207	(30)	79.3	(11.5)	7.86	(0.284)	7	1.3	(0.050)	6.35	(0.250)	1	150	300
Alloy-steel wires:														
Chrome vanadium	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.50	(0.020)	11	(0.435)	1,2	220	425
Chrome silicon	207	(30)	79.3	(11.5)	7.86	(0.284)	5	0.50	(0.020)	9.5	(0.375)	1,2	245	475
Stainless-steel wires:														
Austenitic type 302	193	(28)	69.0	(10)	7.92	(0.286)	2	0.13	(0.005)	9.5	(0.375)	2	260	500
Precipitation hardening 17-7 PH	203	(29.5)	75.8	(11)	7.81	(0.282)	2	0.08	(0.002)	12.5	(0.500)	2	315	600
NiCr A286	200	(29)	71.7	(10.4)	8.03	(0.290)	2	0.40	(0.016)	5	(0.200)	2	510	950
Copper-base alloy wires:														
Phosphor bronze (A)	103	(15)	43.4	(6.3)	8.86	(0.320)	15	0.10	(0.004)	12.5	(0.500)	2	95	200
Silicon bronze (A)	103	(15)	38.6	(5.6)	8.53	(0.308)	7	0.10	(0.004)	12.5	(0.500)	2	95	200
Silicon bronze (B)	117	(17)	44.1	(6.4)	8.75	(0.316)	12	0.10	(0.004)	12.5	(0.500)	2	95	200
Beryllium copper	128	(18.5)	48.3	(7.0)	8.26	(0.298)	21	0.08	(0.003)	12.5	(0.500)	2	205	400
Spring brass, CA260	110	(16)	42.0	(6.0)	8.53	(0.308)	17	0.10	(0.004)	12.5	(0.500)	2	95	200
Nickel-base alloys:														
Inconel alloy 600	214	(31)	75.8	(11)	8.43	(0.304)	1.5	0.10	(0.004)	12.5	(0.500)	2	320	700
Inconel alloy X750	214	(31)	79.3	(11.5)	8.25	(0.298)	1	0.10	(0.004)	12.5	(0.500)	2	595	1100
Ni-Span-C	186	(27)	62.9	(9.7)	8.14	(0.294)	1.6	0.10	(0.004)	12.5	(0.500)	2	95	200
Monel alloy 400	179	(26)	66.2	(9.6)	8.83	(0.319)	3.5	0.05	(0.002)	9.5	(0.375)	2	230	450
Monel alloy K500	179	(26)	66.2	(9.6)	8.46	(0.306)	3	0.05	(0.002)	9.5	(0.375)	2	260	500

Carbon-steel strip:														
AISI 1050	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.25	(0.010)	3	(0.125)	2	95	200
AISI 1065	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.08	(0.003)	3	(0.125)	2	95	200
AISI 1074, 1075	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.08	(0.003)	3	(0.125)	2	120	250
AISI 1095	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.08	(0.003)	3	(0.125)	2	120	250
Bartex	207	(30)	79.3	(11.5)	7.86	(0.284)	7	0.10	(0.004)	1	(0.040)	1	95	200
Stainless-steel strip:														
Austenitic types 301, 302	193	(28)	69.0	(10)	7.92	(0.286)	2	0.08	(0.003)	1.5	(0.063)	2	315	600
Precipitation hardening 17-7 PH	203	(29.5)	75.8	(11)	7.81	(0.282)	2	0.08	(0.003)	3	(0.125)	2	370	700
Copper-base alloy strip:														
Phosphor bronze (A)	103	(15)	43	(6.3)	8.86	(0.320)	15	0.08	(0.003)	5	(0.188)	2	95	200
Beryllium copper	128	(18.5)	48	(7.0)	8.26	(0.298)	21	0.08	(0.003)	9.5	(0.375)	2	205	400

[a]Elastic moduli, density, and electrical conductivity can vary with cold work, heat treatment, and operating stress. These variations are usually minor but should be considered if one or more of these properties is critical.

[b]Diameters for wire; thicknesses for strip.

[c]Typical surface quality ratings. (For most materials, special processes can be specified to upgrade typical values.)
1. Maximum defect depth: 0 to 0.5% of *d* or *t*.
2. Maximum defect depth: 1.0% of *d* or *t*.
3. Defect depth: less than 3.5% of *d* or *t*.

[d]Maximum service temperatures are guidelines and may vary owing to operating stress and allowable relaxation.

[e]Music and hard drawn are commercial terms for patented and cold-drawn carbon-steel spring wire.

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Oil-tempered MB grade, ASTM A229 (0.60 to 0.70 percent C). A general-purpose spring steel, frequently used in coiled form. It is not good with shock or impact loading. Can be formed in annealed condition and hardened by heat treatment. Forms a scale, which must be removed if the material is plated.

Hard-drawn MB grade, ASTM A227 (0.60 to 0.70 percent C). Used where cost is essential. Not to be used where long life and accuracy of loads and deflections are important. Can be readily plated.

Oil-tempered HB grade, SAE 1080 (0.75 to 0.85 percent C). With the exception of a higher carbon content and higher tensile strength, this spring steel is almost the same as the previously described MB grade. It is used for more precise work, where a long life, high fatigue, and high endurance properties are needed. If such aspects are not required, an alloy spring steel should be used in replacement.

12-1-1-2 High-Carbon Spring-Steel Strip. The two main types of springs steel in this group are used with an absolute majority of all flat spring. However, both are susceptible to hydrogen embrittlement even when plated and baked afterward.

Cold-rolled blue-tempered spring steel, SAE 1074, plus 1064 and 1070 (0.60 to 0.80 percent C). This steel can be obtained in its annealed or tempered condition. Its hardness should be within 42 to 46 Rockwell hardness Scale C.

Cold-rolled, blue-tempered spring steel, SAE 1095 (0.90 to 1.05 percent C). It is not advisable to purchase annealed, as this type of steel does not always harden properly and spring properties obtained after forming may be marginal. Its hardness range is 47 to 51 Rockwell hardness Scale C.

12-1-1-3 Alloy Spring Steel. A good spring steel for a high-stress application, with impact loading and shock application involved.

Chromium vanadium steel, ASTM A231 takes higher stresses than high-carbon steel. It also has a good fatigue strength and endurance.

Chromium silicon steel, ASTM A401. This material can be groomed to high tensile stress through heat treatment. Applicable where long life is required in combination with shock loading.

12-1-1-4 Stainless Spring Steel. A corrosion-resistant material. With the exception of the 18-8 type, none of these steels should be used for lower-than-zero temperature applications. High-temperature tolerance is up to 550°F.

Stainless spring steel 302, ASTM A313 (18 percent Cr, 8 percent Ni). This material has quite uniform properties and the highest tensile strength of the group. It can be obtained as cold drawn, since it cannot be hardened by heat treatment. The slight magnetic properties are due to cold working, as in annealed form it is nonmagnetic.

Stainless spring steel 304, ASTM A313 (18 percent Cr, 8 percent Ni). Because of its slightly lower carbon content, this material is easier to draw. Its tensile strength is somewhat lower than that of type 302, even though their other properties coincide.

Stainless spring steel 316, ASTM A313 (18 percent Cr, 12 percent Ni, 2 percent Mo). Less corrosion-prone than the 302 type stainless, with its tensile strength about 12 percent lower. Otherwise it is quite similar to the 302 type.

Stainless spring steel 17-7 PH, ASTM A313 (17 percent Cr, 7 percent Ni, with trace amounts of aluminum and titanium). The tensile strength of this material is almost as high as that of music wire. This is achieved through forming in a medium hard condition and precipitation hardening at low temperatures.

Stainless spring steel 414, SAE 51414 (12 percent Cr, 2 percent Ni). Its tensile strength is approximately the same as that of type 316 (above), and it may be hardened

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through heat treatment. In a high-polished condition this material resists corrosion quite well.

Stainless spring steel 420, SAE 51420 (13 percent Cr). May be obtained in the annealed state, hardened and tempered. Scales in heat treatment. Its corrosion-resistant properties emerge only after hardening. Clear bright surface finish enhances its corrosion resistance.

Stainless spring steel 431, SAE 51431 (16 percent Cr, 2 percent Ni). This material has very high tensile properties, almost on a par with music wire. Such a characteristic is achieved through a combination of heat treatment, followed by cold working.

12-1-1-5 Copper-Base Spring Alloys. This group of spring materials is more expensive than alloy steels or high-carbon materials. They are, however, very useful for their good corrosion resistance and superb electrical properties. An additional advantage is their usefulness in lower-than-zero temperatures.

Spring brass, ASTM B134 (70 percent Cu, 30 percent Zn) cannot be hardened by heat treatment and has generally quite poor spring qualities. Even though it does not tolerate temperatures higher than 150°F, it performs well at subzero. It is the least expensive copper-base spring material, with the highest electrical conductivity, out-weighed by its low tensile strength.

Phosphor bronze (a tin bronze), ASTM B159 (95 percent Cu, 5 percent Sn). This is the most popular copper-based spring material. Its popularity is due to its favorable combination of electrical conductivity, corrosion resistance, good tensile strength, hardness, and low cost.

Beryllium copper, ASTM B197 (98 percent Cu, 2 percent Be) is the most expensive material of this group. It is better formed in its annealed condition and precipitation hardened afterward. The hardened material turns brittle and does not take additional forming. The material has a high hardness and tensile strength. It is used where electrical conductivity is of importance.

12-1-1-6 Nickel-Base Spring Alloys. These alloys take both extremes in temperature, extremely hot and extremely cold, while being corrosion-resistant. For their high resistance to electricity the materials should not be used with electric current. Their field of application lies with precise measuring instruments such as gyroscopes.

Monel (67 percent Ni, 30 percent Cu) cannot be hardened by heat treatment. Its high tensile strength and hardness is obtained through cold drawing and cold rolling. It is almost nonmagnetic and withstands stresses comparable to those beryllium copper can handle. It is the least expensive material of this group.

K-Monel (66 percent Ni, 29 percent Cu, 6 percent Al). The material is nonmagnetic, and the small amount of aluminum makes it a precipitation-hardening applicant. Otherwise it is very similar to previously described monel. It can be formed soft and hardened afterward by application of an age-hardening heat treatment.

Inconel (78 percent Ni, 14 percent Cr, 7 percent Fe) has higher tensile strength and hardness than K-monel, both of these properties being attributable to cold drawing and cold rolling, as it cannot be hardened by heat treatment. It can be used at temperatures of up to 700°F. It is a very popular alloy because of its corrosion resistance, even though its cost is higher than that of the stainless-steel group, yet not so costly as beryllium copper.

Inconel-X (70 percent Ni, 16 percent Cr, 7 percent Fe, with small amounts of titanium, columbium, and aluminum). This nonmagnetic material should be precipitation hardened at high temperatures. It is operable up to 850°F.

Duranickel (98 percent Ni) takes slightly lower temperatures than inconel. It is nonmagnetic, resistant to corrosion, and has a high tensile strength. It can be precipitation hardened.

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12-1-2 Heat Treatment of Springs

Heat treatment of finished springs is done in two stages. First, following the forming process, a low-temperature heat treatment of 350 to 950°F (175 to 510°C) is applied. Such a treatment causes the material to stabilize dimensionally, while removing some residual stresses developed during the forming operation. Residual stresses come in two groups: Some of them are beneficial to the part's functionality; others are detrimental to it.

A second heat treatment is done at higher temperatures, ranging between 1480 and 1650°F (760 and 900°C). This heat treatment strengthens the material, which is still annealed after forming. Typical heat-treatment temperatures for specific materials are shown in Table 12-2. Usually, a 20 to 30-min-long exposure to these temperatures is considered adequate.

TABLE 12-2 Typical Heat Treatment for Springs after Forming

Materials	Heat treatment	
	°C	°F
Patented and cold-drawn steel wire	190–230	375–450
Tempered steel wire:		
Carbon	260–400	500–750
Alloy	315–425	600–800
Austenitic stainless-steel wire	230–510	450–950
Precipitation-hardening stainless wire (17-7 PH):		
Condition C	480/1 h	900/1 h
Condition A to TH 1050	760/1 h, cool to 15°C, followed by 565/1 h	1400/1 h, cool to 60°F, followed by 1050/1 h
Monel:		
Alloy 400	300–315	575–600
Alloy K500, spring temper	525/4 h	980/4 h
Inconel:		
Alloy 600	400–510	750–950
Alloy X-750:		
No. 1 temper	730/16 h	1350/16 h
Spring temper	650/4 h	1200/4 h
Copper-base, cold-worked (brass, phosphor bronze, etc.)	175–205	350–400
Beryllium copper:		
Pretempered (mill hardened) solution	205	400
Annealed, temper rolled or drawn	315/2–3 h	600/2–3 h
Annealed steels:		
Carbon (AISI 1050 to 1095)	800–830*	1475–1525*
Alloy (AISI 5160H 6150, 9254)	830–885*	1525–1625*

*Time depends on heating equipment and section size. Parts are austenitized, then quenched and tempered to the desired hardness.

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Hardened high-carbon steel parts, when electroplated, are prone to cracking. This is caused by the action of hydrogen atoms, which intermingle with the material's metallic lattice and affect its structure. Such an occurrence is called hydrogen embrittlement. To prevent hydrogen embrittlement in plated springs, heat treatment at low temperatures is used prior to plating, with a baking operation added after forming.

Beryllium copper is strengthened after forming by the application of an age-hardening process; with other materials, tempering may sometimes be utilized.

12-1-3 Corrosion Resistance

Coatings (zinc, cadmium, and their alloys) are frequently utilized to prevent corrosion damage to springs. These coatings not only act as a blockade between the material and the outside environment. They also protect the part cathodically, often even when scratched or otherwise topically damaged.

Electroplating is another method of protection used with application of metallic coatings. This type of surface finish, however, causes hydrogen embrittlement to appear, and care should be taken to minimize the part's susceptibility. As a means of protection, there should be no stress points in the part, such as sharp corners, sharp bends, or sharp-cornered cuts. Hardness should be at the minimum allowable level, and residual stresses within the material should be relieved by application of the highest possible heat-treating temperatures. After plating, parts should be baked at low temperatures for approximately 2 to 3 h.

Mechanical plating offers an adequate amount of protection against corrosion and hydrogen embrittlement as well. Such surface treatment should be used for parts suffering from high residual stresses after the forming operation. Its drawback lies in the difficulties with plating of tight or inaccessible areas—all part surfaces must be well exposed and clean.

12-1-4 Fatigue and Reliability

Fatigue in springs is a process that develops slowly and insidiously over the span of three stages: (1) crack induction, (2) crack increase, and (3) failure of the material. It is obvious that fatigue is an irreversible process, detrimental to the functionability of the part. Its development is caused by the emergence of cyclic stresses, accompanied by plastic strains, so common in springs. It may also be caused by the quenching process during springs manufacture.

Residual stresses, as found in the spring material after bending, may either increase or diminish its fatigue resistance. This variation in their influence is due to the fact that there actually are two types of residual stresses within the material.

Stresses which counterbalance those accompanying the spring operation are beneficial to the part's longevity. For example, in a compressed coil spring, where a residual tension is encountered at its core, some residual stresses of the compressive type should ideally be near its surface. A condition like this may create an environment within the material of the spring, allowing for increased loads and improving the spring's resistance to fatigue.

However, if the residual stresses are in another (opposite) direction, their contribution to the load-carrying capacity and fatigue resistance of the spring will be negative.

Favorable residual stresses are often introduced to the spring material by the spring manufacturer. After the first stress-relieving heat treatment, a slight plastic deformation is purposely caused to the parts, following the direction of the spring's own elastic deformation later in service. Unfortunately, such prestressing cannot be preformed with all springs, as its subsequent increase in production costs cannot always be justified.

Plated steel springs emerge from the plating operation free from residual stresses, which cannot be reintroduced afterward.

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For removal of various residual stresses located near the surface, shot peening is utilized. This procedure, however, decreases the load-carrying capacity of the spring, as it lowers the material's yield strength.

Reliability is a fatigue-dependent value, where the decrease in the spring's reliability is always caused by defects produced by fatigue.

Reliability of springs operating at higher temperatures is negatively influenced by so-called *stress relaxation*. It is the decrease in the load-carrying capacity and deflecting capacity of a spring held or cycled under a load. Higher temperatures also affect the tensile strength, fatigue, and modulus of the material.

Stresses and high operating temperatures will in time produce stress relaxation in springs. In opposition to such an influence is the type of alloy: More alloyed materials were found less susceptible to the damage caused by temperature increases.

In static applications, the load-carrying ability of a spring may be impaired by its yield strength and resistance to stress relaxation. To increase the static load-carrying capacity, a longer than necessary spring length should be selected and precompressed to solid in assembly. This process is called *set removal* or *presetting* of the spring, and it may increase the load-carrying ability by 45 to 65 percent. By presetting the spring, favorable residual stresses are introduced into the material. Their type and direction correspond with the spring's own natural (elastic) deformation, attributable to its function.

12-2 SPRINGS IN DIE DESIGN

Types of springs most often used in die and fixture design are coil springs of the compression type. Marginally, extension coil springs and flat springs are utilized.

Compression springs are wound as an open helix (Fig. 12-1) with an open pitch to resist the compressive force applied against it. Overall shapes of these springs are most often straight and cylindrical. But variations in the outline and winding, such as barrel-shaped, conical, hourglass, and variable-pitch springs can be encountered (Fig. 12-2).

Extension springs form a tight helix, and their pitch is limited to the wire thickness (Fig. 12-3). Flat springs may come in many types and shapes (Fig. 12-4).

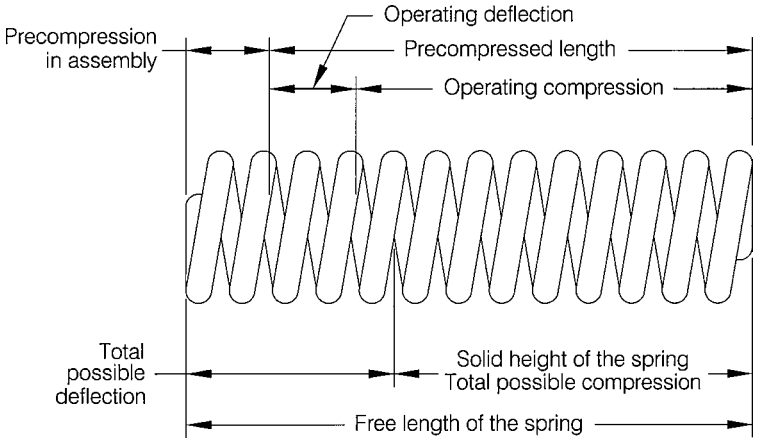

FIGURE 12-1 Compression spring and its properties.

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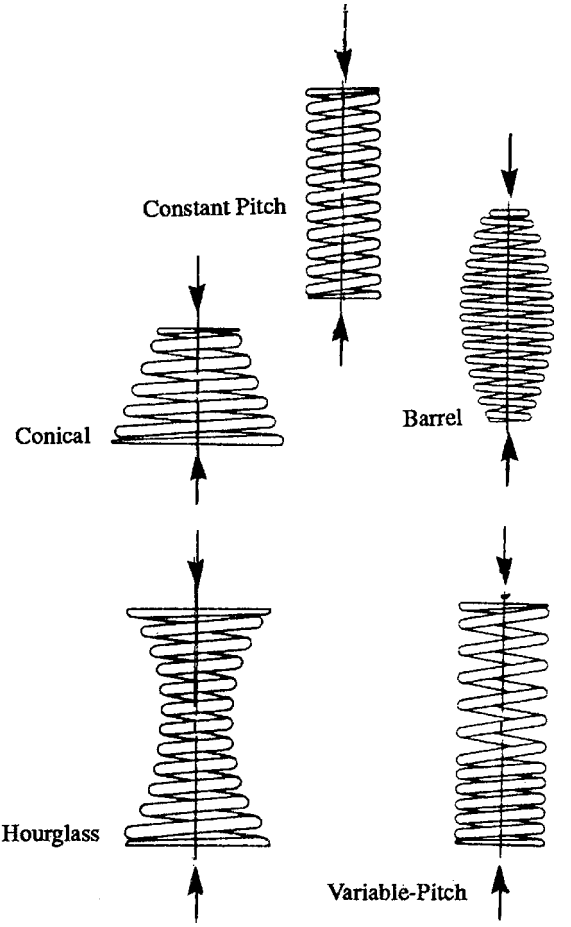

FIGURE 12-2 Helical compression springs, round and rectangular wire. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

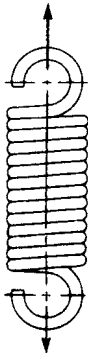

FIGURE 12-3 Helical extension spring. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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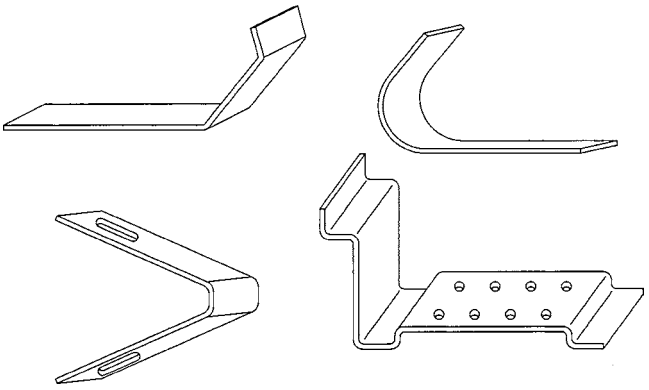

FIGURE 12-4 Flat spring samples.

12-3 HELICAL COMPRESSION SPRINGS

These are abundant in die and fixture design, being used to support spring pads, spring strippers, and other spring-loaded arrangements.

12-3-1 Spring-Related Terminology

A certain terminology has been developed over the years, describing various spring attributes, which is used throughout the industry. Terms like *spring diameter, mean diameter, pitch, squareness*, and *parallelism*, among others, are explained further in the text.

Spring diameter can be either the outside diameter (OD) or inside diameter (ID) or mean diameter (D) of the spring. Mean diameter is equal to the value of OD plus ID divided by 2. It is used for calculations of stress and deflection.

Where the OD is specified, the number is given with regard to the spring's working environment, in this case the cavity, where the spring would be retained. With specification of ID, the size of the coil-supporting pin, which is to fit inside the coil, is important.

Minimum clearances between the spring and its cavity or between the spring and the supporting pin (per diameter) are

$$0.10D \text{ where } D_{\text{cavity}} \text{ is less than 0.512 in. (13 mm)}$$

$$0.05D \text{ where } D_{\text{cavity}} \text{ is greater than 0.512 in. (13 mm)}$$

This is to allow for the increase in diametral size which occurs with the load application on the spring. This increase, seen as a bulging of the spring, is usually quite small, yet it must be taken into account if the function of the spring is not to be impaired. To calculate the increase in size, the following formula is provided:

$$\text{OD}_{\text{solid}} = \sqrt{D^2 + \frac{p^2 - d^2}{\pi^2}} + d \tag{12-1}$$

where the values are as shown in Fig. 12-5.

12-3-1-1 Buckling of Compression Springs. Long springs may buckle unless they are supported by a pin coming through their center. Buckling may occur where the length of a spring unsupported by any pin exceeds the value of *four times its diameter*. Critical buckling

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SPRINGS, THEIR DESIGN AND CALCULATIONS

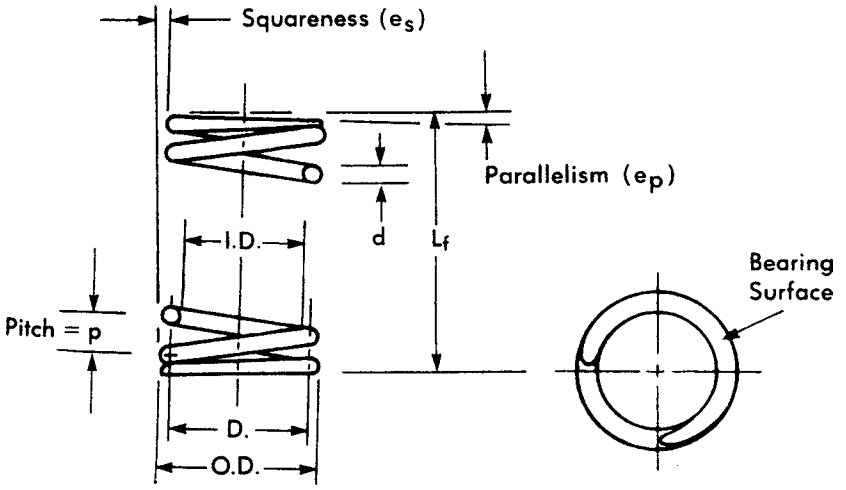

FIGURE 12-5 Dimensional terminology for helical compression springs. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.)*

conditions are given in Fig. 12-6. Critical buckling will occur with values to the right of each line.

Curve *A* depicts those springs whose one end is positioned against a flat plate while its other end is free to tip, as shown in Fig. 12-7. This curve limits the occurrence of buckling conditions to the right and above its location.

Buckling occurrence is lower in springs retained between two parallel plates, as shown in section *B* of Fig. 12-7. *B*-line buckling, as observed in the graph in Fig. 12-6, is lessened accordingly.

In cases where large deflections are required, several springs supported by an inner core consisting of rods or shoulder screws may be utilized.

Spring index C is the ratio of mean diameter to the wire diameter, or

$$C = \frac{D}{d} \tag{12-2}$$

With spring cross sections other than round, this formula is altered as shown in Fig. 12-8.

The preferable spring index value is 4 to 12. Springs with high indexes may become tangled, requiring individual packaging for shipment, especially where their ends are not squared. Springs with indexes lower than 4 are difficult to form.

12-3-1-2 Types of Spring Ends. A wide variety of spring ends may be selected, such as plain ends, plain ends ground, square ends, and square ends ground (Fig. 12-9).

A bearing surface of at least 270° serves to reduce buckling. Squared and ground spring ends have a bearing surface of 270 to 330°. Additional grinding of these ends is undesirable, as it may result in further thinning of these sections.

Springs with squared ends only, where no grinding is involved, are naturally cheaper. This type of end should be reserved to springs with

- Wire diameters less than 0.020 in. (0.5 mm)
- Index numbers greater than 12
- Low spring rates

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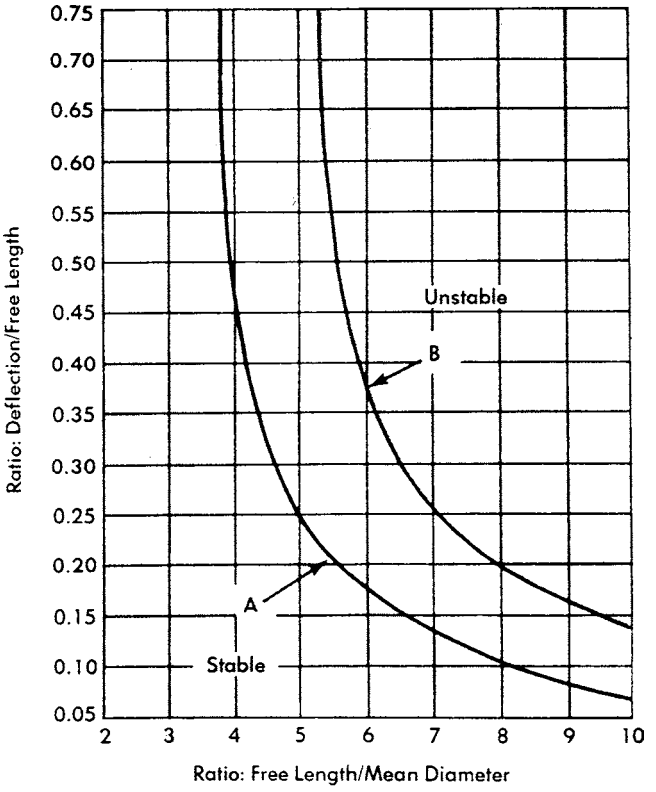

FIGURE 12-6 Critical buckling condition curves. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

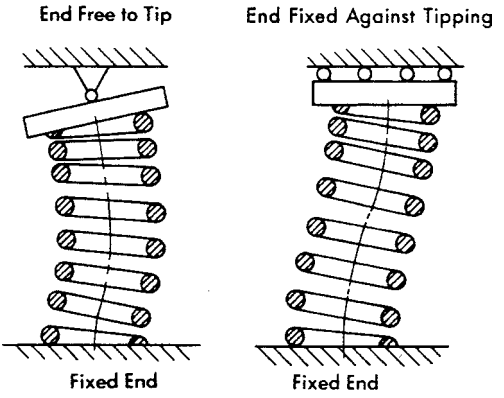

FIGURE 12-7 End conditions used to determine critical buckling. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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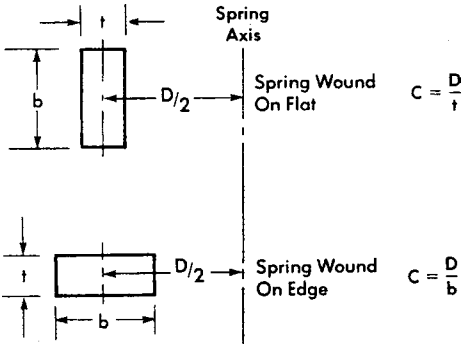

FIGURE 12-8 Rectangular wire compression spring wound on flat or edge. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

12-3-1-3 Number of Active Coils N_a. Springs with squared ends have the number of active coils approximately equal to the total number of coils minus 2. Springs with plain ends usually have more of their coils active, the exact number being dependent on their seating method. Guidelines for selection of end types for a particular spring application are given in Table 12-3.

12-3-1-4 Solid Height. Solid height of a spring is the length of all coils, pressed together. Solid height of a ground spring can be obtained by multiplying the coil diameter by the number of coils. Nonground springs have solid height equal to the number of coils plus 1, multiplied by the wire diameter.

Plating or other coating will increase the solid height of a spring. The safe amount to add for such an increase is approximately one-half of the wire diameter per spring.

12-3-1-5 Direction of Coiling. Helical compression springs are either right- or left-hand wound (Fig. 12-10).

To assess the direction of coiling, the index finger of the right hand should be bent to resemble the shape of a coiled spring, with its tip ending in approximately the same location as the end of the coil. Such a spring, if matching the finger's arrangement, is right-hand-wound. An opposite-side arrangement is a left-hand-wound spring.

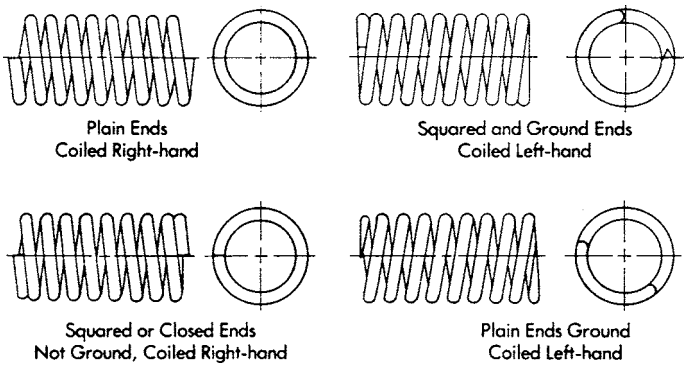

FIGURE 12-9 Types of ends for helical compression springs. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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TABLE 12-3 Guidelines for Dimensional Characteristics of Compression Springs

Dimensional characteristics	Type of ends			
	Open or plain (not ground)	Open or plain (ground)	Squared only	Squared and ground
Solid height L_s	$(N_t + 1)d$	$N_t d$	$(N_t + 1)d$	$N_t d^*$
Pitch p	$\dfrac{L_f - d}{N_a}$	$\dfrac{L_f}{N_t}$	$\dfrac{L_f - 3d}{N_a}$	$\dfrac{L_f - 2d}{N_a}$
Active coils N_a	$\dfrac{L_f - d}{p}$	$\dfrac{L_f}{p} - 1$	$\dfrac{L_f - 3d}{p}$	$\dfrac{L_f - 2d}{p}$
Total coils N_t	N_a	$N_a + 1$	$N_a + 2$	$N_a + 2$
Free length L_f	$p\,N_t + d$	$p\,N_t$	$p\,N_a + 3d$	$p\,N_a + 2d$

*For small index springs lower solid heights are possible.
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12-3-1-6 Squareness and Parallelism. Squared and ground springs are usually square within 3° when measured in their free form. However, squareness of free springs may differ from those under a load.

Parallelism has a considerable effect on the function of an unsupported spring. For illustration of squareness and parallelism, refer to Fig. 12-5.

12-3-1-7 Hysteresis. Hysteresis means the loss of mechanical energy in a spring, which is exposed to cyclic loading and unloading within its elastic range. The known reason for such behavior is the friction between coils, or the friction between the spring and its support during compression.

12-3-2 Variable-Diameter and Variable-Pitch Springs

Variable-diameter springs are as shown in Fig. 12-2, respectively conical, hourglass, and barrel-shaped springs, are utilized where the solid height of the spring must be low or where greater lateral stability and resistance to surging are needed.

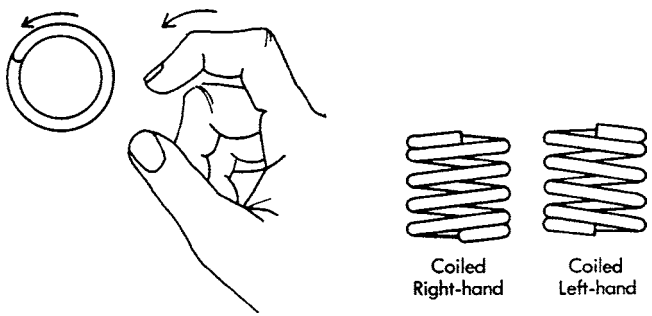

FIGURE 12-10 Direction of coiling of helical compression springs. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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SPRINGS, THEIR DESIGN AND CALCULATIONS

The conical spring's solid height may be as low as one coil diameter, for these springs can be designed in such a fashion as to allow each coil to nest in the preceding coil. The spring rate can be made uniform by varying the pitch along the spring length.

When calculating the highest amount of stress at a predetermined load, the mean diameter of the largest active coil should be used.

Solid height of a spring L_S, made from a round wire, tapered in shape but not telescoping, with its ends squared and ground, can be estimated by using the formula

$$L_S = N_a\sqrt{d^2 - u^2} + 2d \tag{12-3}$$

where u is equal to

$$u = \frac{\text{OD large end} - \text{OD small end}}{2N_a}$$

where N_a is the number of active coils. To approach this calculation properly, each spring has to be considered to amount to several springs in series. Equation (12-11) may be used for such a purpose.

Barrel-shaped and hourglass springs can be calculated the same way, considering them to be two conical springs, which they incidentally are.

Variable-pitch springs are utilized where the natural spring frequency is near or corresponds with that of the cyclic rate of the load application. As coils of lesser pitch become inactive during the spring's function, the natural frequency of the spring will change. This will result in minimizing of surging and spring resonance. Spring resonance is addressed in Sec. 12-4-6.

12-3-3 Commercial Tolerances

Standard commercial tolerances for free length of a spring, diameter, and load are presented in Tables 12-4, 12-5, and 12-6. These tolerances are a good combination of the manufacturing costs and the spring's quality and performance.

TABLE 12-4 Free Length Tolerances of Squared and Ground Helical Compression Springs

Number of active coils per in. (mm)	Tolerances: ± in./in. of free length						
	Spring index (D/d)						
	4	6	8	10	12	14	16
0.02 (0.5)	0.010	0.011	0.012	0.013	0.015	0.016	0.016
0.04 (1)	0.011	0.013	0.015	0.016	0.017	0.018	0.019
0.08 (2)	0.013	0.015	0.017	0.019	0.020	0.022	0.023
0.2 (5)	0.016	0.018	0.021	0.023	0.024	0.026	0.027
0.3 (8)	0.019	0.022	0.024	0.026	0.028	0.030	0.032
0.5 (12)	0.021	0.024	0.027	0.030	0.032	0.034	0.036
0.6 (15)	0.022	0.026	0.029	0.032	0.034	0.036	0.038
0.8 (20)	0.023	0.027	0.031	0.034	0.036	0.038	0.040

For springs less than 12.7 mm (0.500 in) long, use the tolerances for 12.7 mm (0.500 in). For closed ends not ground, multiply above values by 1.7.

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TABLE 12-5 Coil Diameter Tolerances of Helical Compression and Extension Springs

Wire dia, mm (in.)	Tolerances: ± mm (in.)						
	Spring index (D/d)						
	4	6	8	10	12	14	16
0.38 (0.015)	0.05 (0.002)	0.05 (0.002)	0.08 (0.003)	0.10 (0.004)	0.13 (0.005)	0.15 (0.006)	0.18 (0.007)
0.58 (0.023)	0.05 (0.002)	0.08 (0.003)	0.10 (0.004)	0.15 (0.006)	0.18 (0.007)	0.20 (0.008)	0.25 (0.010)
0.89 (0.035)	0.05 (0.002)	0.10 (0.004)	0.15 (0.006)	0.18 (0.007)	0.23 (0.009)	0.28 (0.011)	0.33 (0.013)
1.30 (0.051)	0.08 (0.003)	0.13 (0.005)	0.18 (0.007)	0.25 (0.010)	0.30 (0.012)	0.38 (0.015)	0.43 (0.017)
1.93 (0.076)	0.10 (0.004)	0.18 (0.007)	0.25 (0.010)	0.33 (0.013)	0.41 (0.016)	0.48 (0.019)	0.53 (0.021)
2.90 (0.114)	0.15 (0.006)	0.23 (0.009)	0.33 (0.013)	0.46 (0.018)	0.53 (0.021)	0.64 (0.025)	0.74 (0.029)
4.34 (0.171)	0.20 (0.008)	0.30 (0.012)	0.43 (0.017)	0.58 (0.023)	0.71 (0.028)	0.84 (0.033)	0.97 (0.038)
6.35 (0.250)	0.28 (0.011)	0.38 (0.015)	0.53 (0.021)	0.71 (0.028)	0.90 (0.035)	1.07 (0.042)	1.24 (0.049)
9.53 (0.375)	0.41 (0.016)	0.51 (0.020)	0.66 (0.026)	0.94 (0.037)	1.17 (0.046)	1.37 (0.054)	1.63 (0.064)
12.70 (0.500)	0.53 (0.021)	0.76 (0.030)	1.02 (0.040)	1.57 (0.062)	2.03 (0.080)	2.54 (0.100)	3.18 (0.125)

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The squareness tolerances, as noted, is 3°. Spring life is presented in lieu of fatigue values.

12-4 CALCULATION OF COMPRESSION SPRINGS

All spring design begins with the application of Hooke's law. This law states that any force acting upon the material is directly proportional to the material's deflection, provided such deflection is within the range of that material's elastic limit.

12-4-1 Stress Calculation

Compression springs made of round wire subject this wire to a stress classified as a torsional stress. The basic formula to calculate such a stress S is, according to Bernoulli-Euler,

$$S = \frac{Mc}{J} \tag{12-4}$$

where c = distance from neutral axis at center of section to outside of material, or one-half of material thickness for a round wire
J = polar moment of inertia

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TABLE 12-6 Load Tolerances of Helical Compression Springs

	Tolerances: ±% of load. Start with tolerance from Table 12-4, multiplied by L_F														
	Deflection from free length to load, mm (in.)														
Length tolerance, ±mm (in.)	1.27 (0.050)	2.54 (0.100)	3.81 (0.150)	5.08 (0.200)	6.35 (0.250)	7.62 (0.300)	10.2 (0.400)	12.7 (0.500)	19.1 (0.750)	25.4 (1.00)	38.1 (1.50)	50.8 (2.00)	76.2 (3.00)	102 (4.00)	152 (6.00)
0.13 (0.005)	12	7	6	5											
0.25 (0.010)		12	8.5	7	6.5	5.5	5								
0.51 (0.020)		22	15.5	12	10	8.5	7	6	5						
0.76 (0.030)			22	17	14	12	9.5	8	6	5					
1.0 (0.040)				22	18	15.5	12	10	7.5	6	5				
1.3 (0.050)					22	19	14.5	12	9	7	5.5				
1.5 (0.060)					25	22	17	14	10	8	6	5			
1.8 (0.070)						25	19.5	16	11	9	6.5	5.5			
2.0 (0.080)							22	18	12.5	10	7.5	6	5		
2.3 (0.090)							25	20	14	11	8	6	5		
2.5 (0.100)								22	15.5	12	8.5	7	5.5		
5.1 (0.200)										22	15.5	12	8.5	7	5.5
7.6 (0.300)											22	17	12	9.5	7
10.2 (0.400)												21	15	12	8.5
12.7 (0.500)												25	18.5	14.5	10.5

First load test at not less than 15% of available deflection.
Final load test at not more than 85% of available deflection.
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Polar moment of inertia for a round section is

$$J = \frac{\pi d^4}{32}$$

where d = wire diameter
M = torsional moment, calculated as follows:

$$M = PR = \frac{PD}{2}$$

where P = load on spring, lb
D = mean diameter

Adding a stress-correcting factor K_W changes this formula to

$$S = \frac{8PD}{\pi d^3} K_W = \frac{2.546PD}{d^3} K_W \tag{12-5}$$

The sudden emergence of the stress-correcting factor K_W is due to the nonuniform distribution of torsional stress across the cross section of the wire. This is caused by the curvature of the coil and a direct shear load. Maximum torsional stress can be found at the inner surface of the spring, and its value is assessed with the aid of stress-correcting factor K_{W1} or K_{W2} (see Table 12-7), attributable to Dr. A. M. Wahl of Westinghouse Electric Co. The formula to calculate this correction factor is as follows:

$$K_{W1} = \frac{4C-1}{4C-4} + \frac{0.615}{C} \tag{12-6}$$

In some conditions, where resultant stresses are distributed more uniformly around the cross section, the stress-correcting factor K_{W2} can be used as

$$K_{W2} = 1 + \frac{0.5}{C} \tag{12-7}$$

Where elevated temperatures are encountered in the spring-operating environment, the stress distribution is more uniform around the cross section and can therefore be estimated, referring to Fig. 12-11.

TABLE 12-7 Maximum Allowable Torsional Stresses for Helical Compression Springs in Static Applications

Materials	Max % of tensile strength	
	Before set removed (K_{W1})	After set removed (K_{W2})
Patented and cold-drawn carbon steel	45	60–70
Hardened and tempered carbon and low-alloy steel	50	65–75
Austenitic stainless steels	35	55–65
Nonferrous alloys	35	55–65

Bending or buckling stresses are not included.
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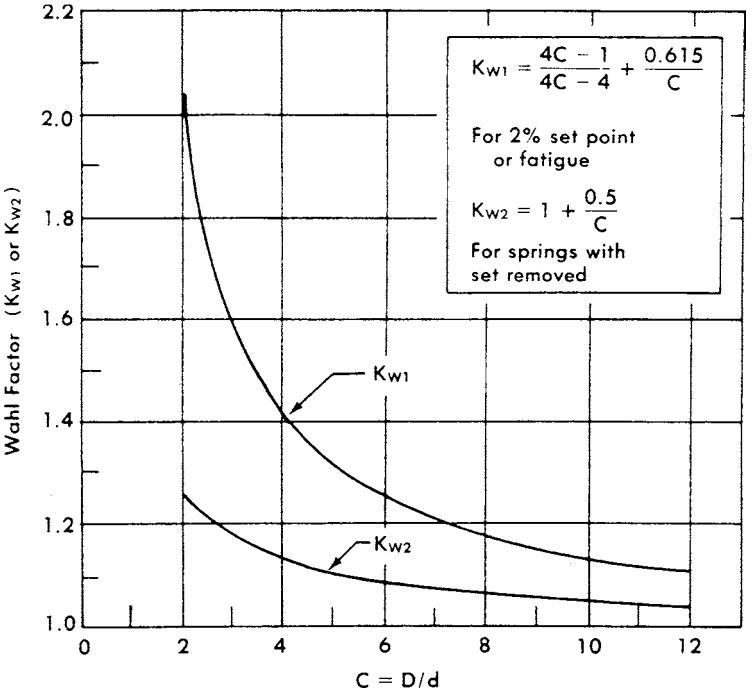

FIGURE 12-11 Wahl stress-correction factors for round wire helical compression and extension springs. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

Maximum allowable torsional stresses for helical compression springs in static applications are as listed in Table 12-7.

12-4-2 Diameter of Wire *d*

To choose the proper wire diameter for a given load, at an assumed stress, Eq. (12-8*a*) may be used.

$$\text{If } S = \frac{2.546PD}{d^3} \qquad \text{then} \qquad d = \sqrt[3]{\frac{2.546PD}{S}} \tag{12-8a}$$

Knowing other pertinent values, we may calculate the spring diameter by using the formula for a round wire:

$$d = \frac{\pi D^2 S N_a}{Gf K_W} \tag{12-8b}$$

where N_a = number of active coils
G = modulus of rigidity
F = deflection, in
K_W = Wahl's correction factor

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whereas a wire of square cross section can be figured out as

$$d = \frac{2.32\,SD^2\,N_a}{Gf\,K_W} \tag{12-8c}$$

where d = length of square side of coil

12-4-3 Deflection *f*

Accordingly, the deflection can be assessed on the basis of previous information by using the stress formula described previously:

$$f = \frac{8PD^3N_a}{Gd^4} \tag{12-9}$$

where N_a = number of active coils
G = modulus of rigidity, usually around 11,500,000 lb/in^2 for steel wire. For typical properties of other materials see Tables 12-1 and 12-8

The modulus of rigidity, also called the modulus of shear, differs from the modulus of elasticity in that it produces an angular shift in the material's atomic structure. The modulus of rigidity and modulus of elasticity are related as follows:

$$E = 2G(1 + \mu) \tag{12-10}$$

where μ = Poisson's ratio

12-4-4 Spring Rate *k*

For helical compression springs, the spring rate is the change in load per unit of deflection:

$$k = \frac{P}{f} = \frac{Gd^4}{8D^3N_a} \tag{12-11}$$

where P = load on spring, lb

Where compression springs are used in parallel, the total rate is equal to the sum of the rates of individual springs. The sum of the rates of compression springs in series is calculable as

$$k = \frac{1}{1/k_1 + 1/k_2 + 1/k_3 + \cdots + 1/k_n}$$

12-4-5 Dynamic Loading, Suddenly Applied Load

Often, not only the influence of slowly applied loads should be figured out with springs. Suddenly applied loads too can have a tremendous impact on the life and performance of a spring. Since the load velocity is usually not exactly known, springs may end up retaining an unknown amount of kinetic energy.

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TABLE 12-8 Typical Properties of Spring Temper Alloy Steel

Material	Tensile strength MPa (10^3 lb/in.^{2})	Rockwell hardness	Elongation,* %	Bend factor* (2*r*/*t* transverse bends)	Modulus of elasticity, 10^4 MPa (10^6 lb/in.^{2})	Poisson's ratio
Steel, spring temper	1700 (246)	C50	2	5	20.7 (30)	0.30
Stainless 301	1300 (189)	C40	8	3	19.3 (28)	0.31
Stainless 302	1300 (189)	C40	5	4	19.3 (28)	0.31
Monel 400	690 (100)	B95	2	5	17.9 (26)	0.32
Monel K500	1200 (174)	C34	40	5	17.9 (26)	0.29
Inconel 600	1040 (151)	C30	2	2	21.4 (31)	0.29
Inconel X-750	1050 (152)	C35	20	3	21.4 (31)	0.29
Copper-beryllium	1300 (189)	C40	2	5	12.8 (18.5)	0.33
Ni-span-C	1400 (203)	C42	6	2	18.6 (27)	
Brass CA 260	620 (90)	B90	3	3	11.0 (16)	0.33
Phosphor bronze	690 (100)	B90	3	2.5	10.3 (15)	0.20
17-7 PH RH950	1450 (210)	C44	6	Flat	20.3 (29.5)	0.34
17-7 PH condition C	1650 (239)	C46	1	2.5	20.3 (29.5)	0.34

*Before heat treatment.

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Considering that work done on springs (= force × space) equals the energy absorbed by the spring when neglecting the hysteresis, the solution is as follows:

For loads applied very slowly:

$$f = \frac{P}{k} \tag{12-12}$$

For loads applied suddenly:

$$f = \frac{2P}{k} \tag{12-13}$$

For loads dropped from a certain height:

$$f = \sqrt{\frac{2P(s+f)}{k}} \tag{12-14}$$

where f = deflection, in
k = spring rate
P = load on the spring, lb
s = height from which the load was dropped, in

12-4-6 Dynamic Loading, Impact

With a spring being cyclically loaded and unloaded, an emergence of surge wave provides for the transmission of torsional stress from the point of loading application to the point of restraint. This surge wave travels at a velocity one-tenth the velocity of a normal torsion stress wave. Velocity of the torsion stress wave V_T can be calculated:

$$V_T = \sqrt{\frac{Gg}{\rho}} \quad \text{in./s} \tag{12-15a}$$

which in metric version becomes

$$V_T = 10.1\sqrt{\frac{Gg}{\rho}} \quad \text{m/s} \tag{12-15b}$$

where ρ = density, 1/1365 for steel
g = acceleration due to gravity, 32 ft/s^2, or 9.8 m/s^2

This surge wave limits the springs' absorption and release of energy by restricting its impact velocity V, which is a function of stress and material constants, applied in parallel with the spring axis.

Impact velocity may be calculated as follows:

$$V \simeq S\sqrt{\frac{g}{2\rho G}} \quad \text{in./S} \tag{12-16a}$$

and in metric:

$$V \simeq 10.1S\sqrt{\frac{g}{2\rho G}} \quad \text{m/s} \tag{12-16b}$$

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SPRINGS, THEIR DESIGN AND CALCULATIONS

Impact velocity and stress are actually independent of the configuration of the spring. For steel materials, impact velocity should be in the range of

$$V = \frac{S}{131} \quad \text{in./s} \qquad \text{or} \qquad V = \frac{S}{35.5} \quad \text{m/s} \tag{12-17}$$

12-4-7 Dynamic Loading, Resonance

Springs have a natural inclination to vibration, creating a resonance within their mass. Resonance occurs where the cyclic loading approaches the natural frequency of the spring or its multiples. Resonance may increase the coil deflection and stress level, exceeding all assumed amounts. It can cause the spring to shiver and bounce, with subsequent alteration of its load-carrying capacity and other values.

A natural spring's frequency must be at least 13 times greater than its operating frequency to prevent the emergence of resonance.

The compression spring's natural frequency is inversely proportional to the amount of time needed for a surge wave to traverse the spring. For a spring which has no damping and has both ends fixed, this amounts to

$$n = \frac{d}{9D^2N_a}\sqrt{\frac{Gg}{\rho}} \tag{12-18a}$$

where the value of n for steel is

$$n = \frac{14{,}000d}{N_a D^2} \tag{12-19a}$$

In metric translation, this calculation becomes

$$n = \frac{1.12\times10^3 d}{D^2N_a}\sqrt{\frac{Gg}{\rho}} \tag{12-18b}$$

where the value of n for steel is

$$n = \frac{3.5\times10^5 d}{D^2N_a} \tag{12-19b}$$

where n = natural frequency, Hz
ρ = density, 1/1365 for steel
g = acceleration due to gravity, 32 ft/s^2, or 9.8 m/s^2

12-5 SPECIAL CROSS SECTIONS OF THE WIRE

Springs whose cross section is rectangular in shape and oriented with the width of the rectangle perpendicular to the spring axis have a capacity to absorb more work energy in smaller space than equivalent round wire. This is true despite the fact that the distribution of stress around the rectangular section may not be quite as uniform as that of the round wire. Rectangular-shaped wire is also more costly than round wire, with the keystoned wire being the most expensive of the three (Fig. 12-12).

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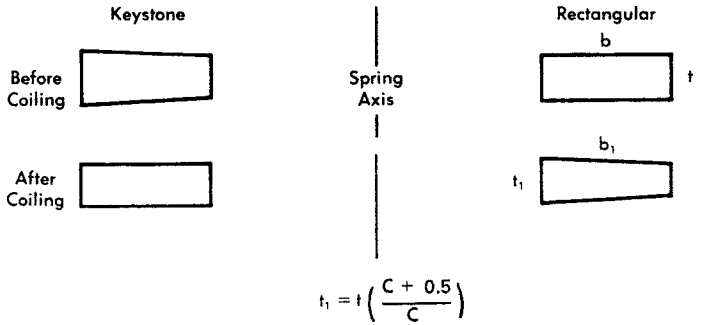

FIGURE 12-12 Wire cross section before and after coiling. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

The coiling operation, when applied to a rectangular wire, alters its shape, slanting the rectangle against one of the sides. Keystone wire is manufactured to come out from coiling rectangular.

Rectangular-shaped wire springs can be calculated with slightly altered round-wire formulas. The rate for such a compression spring is

$$k = \frac{P}{f} = \frac{Gbh^3}{N_a D^3} K_2 \tag{12-20}$$

Since the wire is torsionally loaded, the rate is equal if the wire is wound on flat or on edge (see Fig. 12-8). Values of constants K_1 and K_2 are as shown in Fig. 12-13.

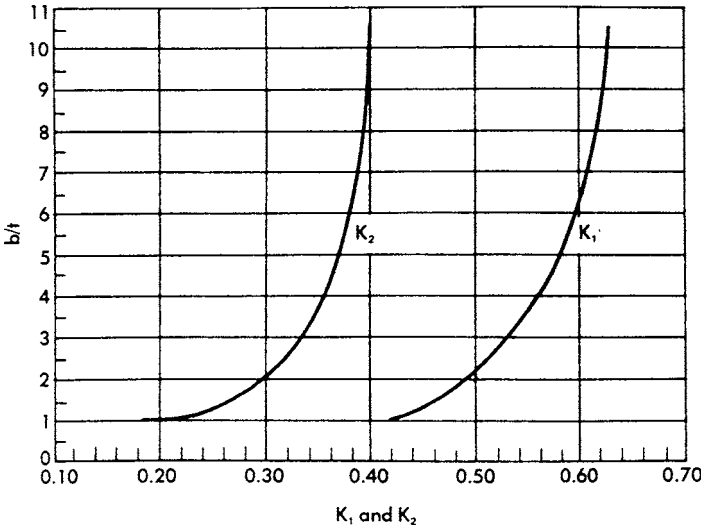

FIGURE 12-13 Constants for rectangular wire in torsion. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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The stress in such a spring can be obtained by using the formula given in Eq. (12-21).

$$S = \frac{PD}{K_1 bh^2} K_E \qquad \text{or} \qquad \frac{PD}{K_1 bh^2} K_F \tag{12-21}$$

where K_E = stress-correcting factor for springs wound on edge, shown in Fig. 12-14
K_F = stress-correcting factor for springs wound on flat, shown in Fig. 12-15

Where an attempt is made to produce a rectangular-shaped wire by rolling a round material, or where the cross-sectional shape of the wire is not quite round, a correction factor h' should be added to the stress formulas above, to replace h:

$$h' = \frac{2d}{1 + b/h} \tag{12-22}$$

To figure out the amount of stress and deflection, a triangular cross section of the wire would utilize the formulas

$$S = \frac{20PR}{l^3} \tag{12-23}$$

where l = length of each side of the triangle (see Fig. 12-16)
R = mean radius of the coil

$$f = \frac{290.3PN_a R^3}{Gl^4} \tag{12-24}$$

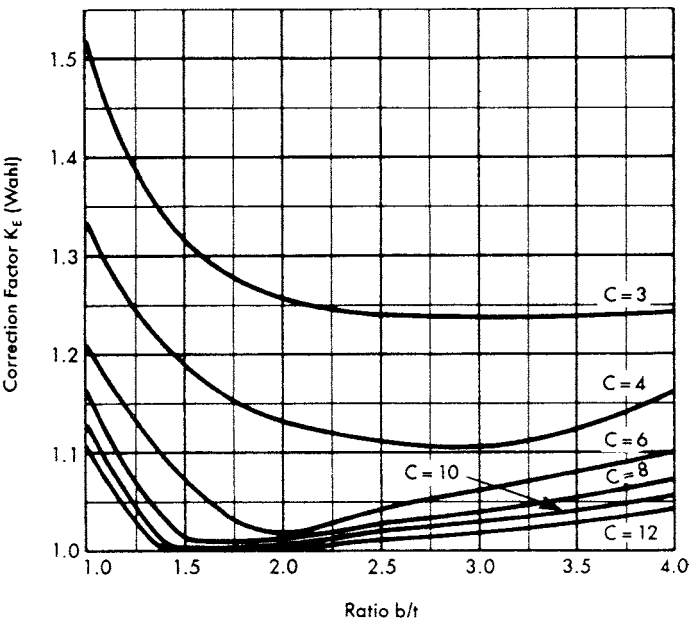

FIGURE 12-14 Stress-correction factors for rectangular wire compression springs wound on edge. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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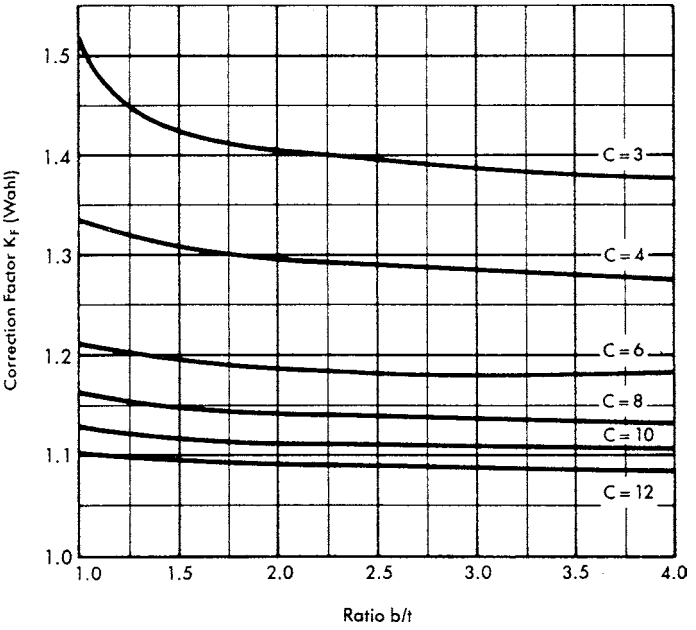

FIGURE 12-15 Stress-correction factors for rectangular wire compression springs wound on flat. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

Hexagonal cross sections, where the inscribed circle's diameter (as shown in Fig. 12-16) is v and the area of the cross section is A, can be calculated by using the following formulas:

$$S = \frac{PR}{0.217Av} \tag{12-25}$$

and

$$f = \frac{47.24PN_aR^3}{Gv^2A} \tag{12-26}$$

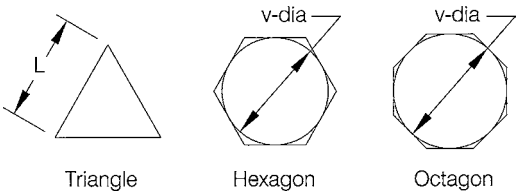

FIGURE 12-16 Cross-sectional shapes.

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For octagonal sections (Fig. 12-16), where the inscribed circle's diameter is v and the area of the cross section is A, the formula is

$$S = \frac{PR}{0.223Av} \tag{12-27}$$

and

$$f = \frac{48.33PN_aR^3}{Gv^2A} \tag{12-28}$$

Figure 12-16 shows triangular, hexagonal, and octagonal cross sections. For a regular elliptical section, the following formulas can be used:

$$S = \frac{16PR}{\pi x^2 y} \tag{12-29}$$

and

$$f = \frac{248.1PN_aR^3J}{GA^4} \tag{12-30}$$

where x = minor axis of ellipse
y = major axis of ellipse
A = cross-sectional area of ellipse
J = polar moment of inertia of the section, which can be calculated as

$$J = \frac{\pi(xy^3 + x^3y)}{64} \tag{12-31}$$

and subsequently,

$$A = \frac{\pi xy}{4} \tag{12-32}$$

12-6 HOT-WOUND SPRINGS

Most often, springs are cold-formed up to 3/8 in. (10 mm) diameter of the wire or bar size. After this dimension, cold forming becomes difficult, and hot winding of springs is used instead. This type of spring manufacture involves heating of the steel up to the austenitic range, winding it, quenching down to martensitic structure, and tempering to arrive at required properties.

The most often used type of hot-wound spring is the compression spring, utilized as a part of an automobile suspension system or as springs used in rail cars.

Marginally some extension, torsion, and volute springs may be hot-wound as well.

12-6-1 Design and Calculations

Design parameters and calculations for this type of spring are the same as those of other springs. The only exception is that of the spring rate calculation, which here

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includes an empirical factor K_H, which is providing for the adjustment due to scaling-caused complications.

$$k = \frac{P}{f} = \frac{Gd^4 K_H}{8D^3 N_a} \tag{12-33}$$

where k = spring rate
P = load, lb
f = deflection, in
G = modulus of rigidity
N_a = number of active coils
K_H = 0.91 for hot-rolled carbon or low-alloy steel materials, which are not centerless ground
= 0.96 for hot-rolled carbon or low-alloy steel materials, centerless ground
= 0.95 for carbon or low-alloy steel material on torsion springs

12-6-2 Types of Spring Ends

The ends of hot-wound springs may be ground, tapered, tangent, or pigtailed, as shown in Fig. 12-17.

Ground ends provide the spring with a good bearing surface and unsurpassed squareness.

Tapered ends are produced by rolling a taper on the bar. During hot winding, these ends must be guided to provide for their proper orientation. Additional grinding improves the spring's squareness and bearing surface quality.

Tangent ends are standard, with no secondary manufacturing procedures involved. Because of the hot-winding process, springs with tangent ends have a straight portion approximately

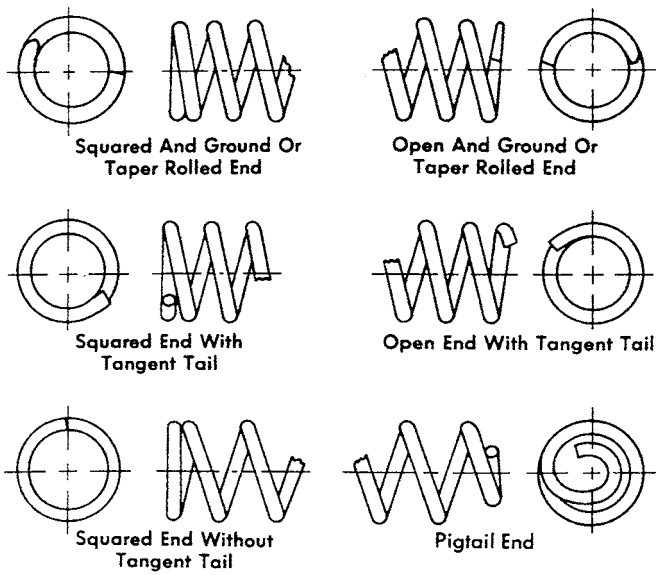
Squared And Ground Or Taper Rolled End
Open And Ground Or Taper Rolled End
Squared End With Tangent Tail
Open End With Tangent Tail
Squared End Without Tangent Tail
Pigtail End

FIGURE 12-17 Typical ends of hot-wound compression springs. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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two wire diameters in size at each end. Their bearing surface must be designed in accordance with the requirements of such a shape, as it tends to exceed the outline of the spring.

Pigtailed ends are formed along with the hot-winding process. These ends are popular in situations where the spring must be clamped or bolted to its seat.

12-6-3 Hot-Wound, Noncompression Springs

Extension and torsion springs, utilizing loops and legs, have these additions to their shapes formed at the same time the spring is wound. For that reason, such shapes should be kept as simple as possible. All elaborate designs that are difficult to achieve involve reaustenitizing of the spring, with subsequent increase in manufacturing costs.

12-7 HELICAL EXTENSION SPRINGS

Helical extension springs are used where a pulling force is needed. They are most often made from round wire, closely wound, with initial tension obtained through stressing them in torsion.

12-7-1 Design of Extension Springs

Design procedures are the same as those of compression springs. It should be remembered, though, that extension springs, when compared to compression-type springs, are slightly different in that they are

- Coiled with initial tension, equal to the minimal amount of force needed to separate adjacent coils
- Coiled (usually) without their set being removed
- Equipped with no fixed stop to prevent their overloading

Figure 12-18 shows typical extension spring dimensions.

12-7-2 Spring Rate of Extension Springs k

Same as for helical compression springs, the spring rate of the extension spring is the change in load per unit of deflection. The formula to be used with extension springs is, however,

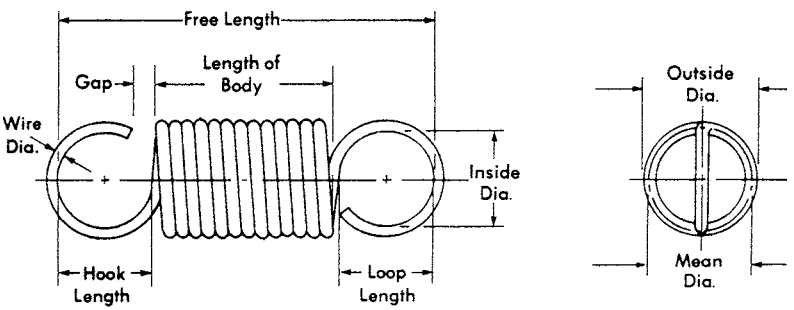

FIGURE 12-18 Typical extension spring dimensions. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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slightly different:

$$k = \frac{P - P_I}{f} = \frac{Gd^4}{8D^3N_a} \tag{12-34}$$

where P_I is the initial tension. The applicable stress is given by the formula

$$S = \frac{8PD}{\pi d^3} K_W \tag{12-35}$$

12-7-3 Types of Spring Ends

A wide variety of ends is utilized with this type of spring as a provision for their attachment to other parts of the assembly. There are twist loops, side loops, cross-center loops, and extended hooks. Loops differ from hooks in that their shape will form small gaps, whereas hooks are actually loops with large gaps.

Special types of ends are formed from straight sections of wire tangent to the spring body shape.

Naturally, common loops of standard lengths are most economical to obtain. Figure 12-19 shows common end configurations for helical extension springs.

Stresses in loops or hooks are often higher than those within the spring wound-up body itself. For that reason, liberal bend radii in loops, combined with reduced end coil diameters, should be used to alleviate this problem.

The stress encountered in a full twist loop may reach its maximal value in bending at point *A* (shown in Fig. 12-20), while the value of the maximum stress in torsion is at its highest at point *B*.

To assess the actual amount of stress at these two locations, the following formulas should be used:

$$S_A = \frac{16DP}{\pi d^3} K_1 + \frac{4P}{\pi d^2} \text{ bending} \tag{12-36a}$$

where

$$K_1 = \frac{4C_1^2 - C_1 - 1}{4C_1(C_1 - 1)} \tag{12-37}$$

and

$$C_1 = \frac{2R_1}{d} \tag{12-38a}$$

and

$$S_B = \frac{8DP}{\pi d^3} \frac{4C_2 - 1}{4C_2 - 4} \tag{12-36b}$$

and

$$C_2 = \frac{2R_2}{d} \text{ torsion} \tag{12-38b}$$

It is recommended that the value of C_2 be greater than 4.

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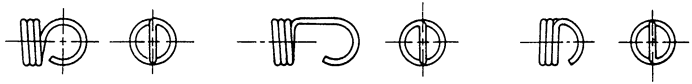
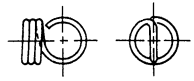
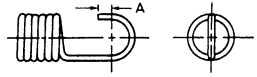
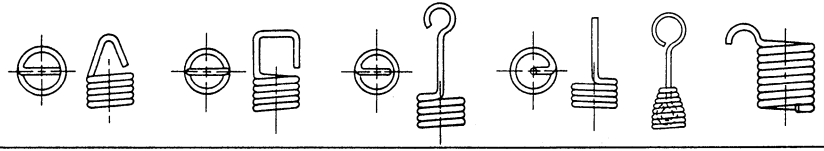
Type	Configurations	Recommended Length* Min.-Max.
Twist Loop or Hook		0.5-1.7 I.D.
Cross Center Loop or Hook		I.D.
Side Loop or Hook		0.9-1.0 I.D.
Extended Hook		1.1 I.D. and up, as required by design
Special Ends		As required by design

* Length is distance from last body coil to inside of end. I.D. is inside diameter of adjacent coil in spring body.

FIGURE 12-19 Common end configurations for helical extension springs. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

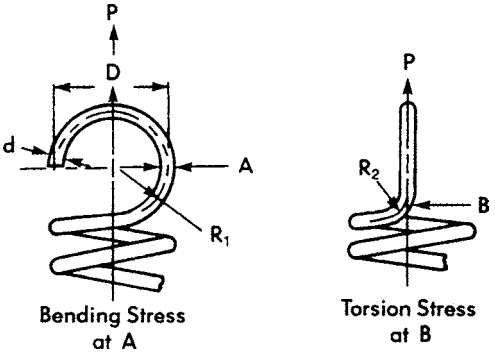


FIGURE 12-20 Location of maximum bending and torsion stresses in twist loops. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

12-7-4 Specific Recommended Dimensions

With the free length of an extension spring being measured between the inner surfaces of both ends (per Fig. 12-18), this dimension should be made equal to the length of the spring body, plus its ends. The spring body can be calculated as

$$L_{\text{body}} = d(N + 1) \tag{12-39}$$

where N = number of coils

The gap in the loop (or hook) opening can vary with the manufacturer. Generally, this gap should not be specified smaller than one-half the wire diameter. If a gap smaller than that is desired, the designer should consult the spring manufacturer about its feasibility.

The number of active extension spring coils is equal to the number of coils it contains. In springs used with threaded inserts and swivel hooks, the number of active coils is lower.

Loops and hooks account for approximately $0.1N_a$ of active coils with one-half twist loops. Up to $0.5N_a$ can be used with some cross-center, full-twist loops, or extended loops.

12-8 FLAT SPRINGS

Flat springs are those made from strip or sheet material. They may contain bends and sometimes their shapes may be quite complex. Often, they perform additional functions in an assembly, such as locating the opening or a part, retaining other parts in an assembly, or banking on them, acting as a latch, or conducting electricity.

The most commonly used flat springs are of a cantilever type (Fig. 12-21). When calculating such springs, all cantilever and simple-beam equations may be used. However, to obtain more accurate results, calculations based on curved beam theory are recommended by Associated Spring's experts. Where the amount of elastic deflection is of importance, Castigliano's method is their additional choice.

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SPRINGS, THEIR DESIGN AND CALCULATIONS

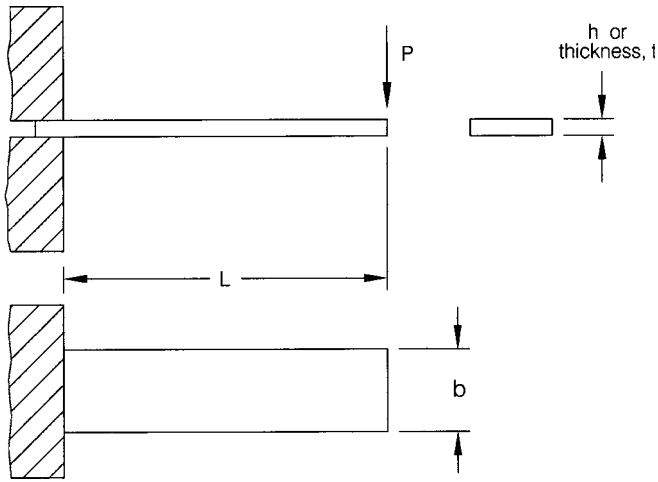

FIGURE 12-21 Cantilever spring.

12-8-1 Materials

Carbon steel materials, most often used in flat spring manufacture, usually belong in one of the following groups:

- 0.70 to 0.80 percent carbon content, which is a slightly less expensive material, more tolerant of sharper bends
- 0.90 to 1.05 percent carbon content with a higher elastic limit

Materials are used either in their annealed form or pretempered. Annealed materials must be heat-treated after forming.

The amount of distortion caused by a heat-treatment is difficult to assess or calculate. Rather, the designer should depend on a spring manufacturer's experience, while avoiding too precise tolerances, sharp corners, and edges on the spring. Parts with thin and wide cross sections will tend to be more distorted, sometimes requiring restriking or other adjusting operation.

Pretempered materials must be hard enough to possess a sufficient elastic limit for their function under desired loads. At the same time, this material should not be too hard, as it may fracture during forming or cause breakage and excessive wear to the tooling. The spring-back of pretempered material is greater, and an allowance for it must be made in the tool designing stage. Again, an experienced spring manufacturer may be the one to evaluate the amount of necessary alterations.

12-8-2 Design and Calculations

Mostly all flat springs are preloaded during the bending operation. The surface condition of the material must be smooth, possibly polished, with no dents or nicks. Sharp edges and burrs should be eliminated by design or by abrasive means. Bend radii should be liberal in size, since sharp radii become stress points, exerting damaging influence on the part. Naturally, all bends should be oriented across the material's grain line.

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Based on Bernoulli-Euler beam theory for bending of beams, the maximum stress can be calculated as

$$S = \frac{Mc}{I} \tag{12-40}$$

where c = distance from neutral axis to outside or one-half of material thickness
M = moment, amounting to distance from support times the load, or $M = PL$
I = moment of inertia. For a rectangular section, moment of inertia can be calculated:

$$I = \frac{bh^3}{12} \tag{12-41}$$

Combining the above values into the single equation, we get the maximum stress expressed as

$$S = \frac{6PL}{bh^2} \tag{12-42}$$

where P = load on the spring, lb
L = length of lever arm, in

The load value may be calculated by using a formula

$$P = \frac{fEbh^3}{4L^3} \tag{12-43}$$

where E = modulus of elasticity
f = deflection, in

For flat springs, where the width to thickness ratio is relatively small, the maximum stress and deflection formulas are reasonably accurate. Higher width to thickness ratio increases the flexural rigidity of the spring, resulting in the modulus of elasticity E being replaced by E' as follows:

$$E' = \frac{E}{1 - \mu^2} \tag{12-44}$$

where μ = Poisson's ratio

The deflection can be calculated using a standard formula

$$f = \frac{PL^3}{3EI} \tag{12-45}$$

where E = modulus of elasticity
I = moment of inertia; for a rectangular section the value can be calculated with Eq. (12-41).

This formula, when applied to a rectangular section, changes to

$$f_{RT} = \frac{4PL^3}{Ebh^3} \quad \text{or} \quad \frac{2SL^2}{3Eh} \tag{12-46}$$

where S = stress

Since L and h values are raised to the third power, accurate measurements are vital.

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All these equations were proved satisfactory where the ratio of deflection to cantilever length F/L was less than 0.3. For larger deflections, E should be replaced by E', as given by Eq. (12-44).

12-9 GAS AND AIR SPRINGS AND THEIR APPLICATIONS

Most probably, forced by an unending and never-resting competition, the industry had to come up with a different type of springs, to ease their installation, improve their function, and remove the "gray areas" of preload from the spring usage dictionary. With the wound springs, special spring pockets had to be milled into the blocks; the correct spring height was an unending problem; and the force buildup, also called preload, was always somewhat a mystery. During the operation, the force of wound springs started from zero and progressed upwards, sometimes becoming unpredictable and often even excessive.

Gas springs are different. They are capable of delivering much more force in lesser area than ordinary wound springs. They generate pressure on contact, eliminating the need for preload. This way the pressure pad can be smaller, the amount of cylinders diminished, the stroke shorter, while the force produced by springs is constant and unwavering alongside the stroke of a press. Their travel to length ratio is much larger and their pressure can be easily monitored.

Gas springs are also more balanced. Whereas in an assembly of several wound springs some may be cracked and the rest may not produce the pressure needed, gas springs are always there, always working. Should their pressure drop somehow, the gas springs can reclaim the gas needed and prop up the pressure to the demanded levels.

Out of all gasses, nitrogen springs gained the ground across the board. One of the reasons may be the low cost of nitrogen gas, but nitrogen is also nonflammable, inert, and tonnage resistant. This means that as the pressure against such spring rises, the force of its output increases in proportion to the volume of gas that was compressed.

Nitrogen springs should never be preloaded, and, actually, manufacturers caution against preload with determination. But at the same token, nitrogen charge should not be lowered in anticipation of extending the life expectancy of the seal. Such a precaution may actually harm the spring, as the modern seals are designed to operate at the full nitrogen charge.

Their loading is of concern though, as they are not to be used at the operating pressure exceeding 90 percent of their recommended maximum.

12-9-1 Nitrogen Springs and Their Types

There are several types of nitrogen spring systems available on the market today, the difference between each group being provided by the method of attachment and gas distribution. These types are as described below:

12-9-1-1 Manifold System. Manifold system is a closed system, embedded in a metal plate, which is cross-drilled to allow for the nitrogen gas distribution. The spring cylinders are attached to the channels through the tapped holes and may be positioned where needed. The whole assembly is connected to the control panel, which directs the volume of gas within the system (See Fig. 12-22).

Manifold systems require clearance between the die and the end of the cylinder rod, so that the rod does not touch the plate of the opposite die half (either upper or lower plate, with dependence on the type of mounting). The clearance is necessary for the piston to come to a full die-open position.

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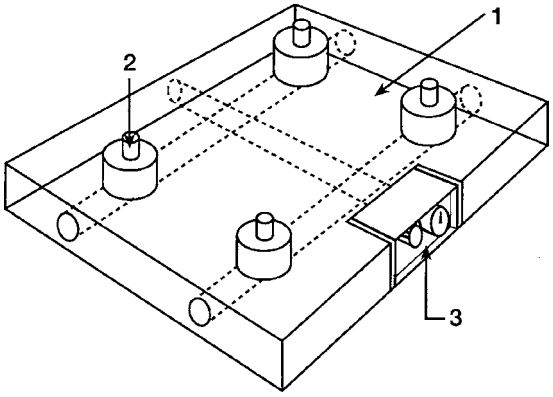

FIGURE 12-22 Nitro Dyne® XP manifold system of gas springs. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

Nitrogen reservoirs can also be added to the bottom die shoe (see Fig. 12-23), if the shut height of the press is too limited. The details of such an arrangement are the same as those of the regular manifold system. The nitrogen reservoir interconnects the cylinders via the holes drilled through the shoe. As can be expected, a demand such as this will weaken the die shoe somewhat.

The compression tank retains the excessive nitrogen, which the springs leak when being pressed down. To determine the tank size, the amount of excessive nitrogen (also called "swept volume") has to be determined first. This can be calculated as:

$$V_{SW} = A_P \times L_{WK} \times No.\ of\ Cylinders \tag{12-47}$$

where V_{SW} = swept volume
A_P = area, piston
L_{WK} = working stroke

From the result, the volume of the tank can be determined as:

$$V_T = V_{SW}(100 : R_P) \tag{12-48}$$

where V_T is the required volume of the tank, and R_P is the percentage of desired pressure rise, or increase.

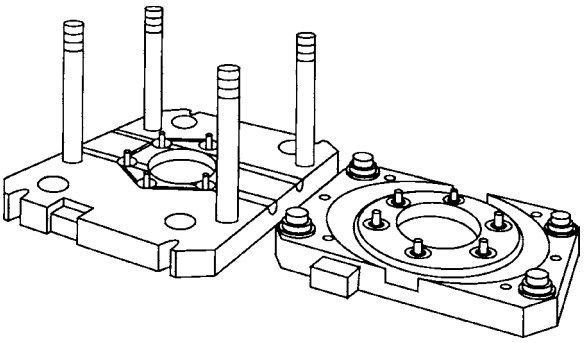

FIGURE 12-23 Nitrogen cylinders as installed in the die shoe. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

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SPRINGS, THEIR DESIGN AND CALCULATIONS

Pressure increase, also called pressure rise, is generally recommended at 15–20 percent for draw dies and 30–40 percent for strippers, form pads, and cam returns.

12-9-1-2 Hose and Tank System. In this design, a reservoir tank is connected with cylinders via high-pressure hoses. The whole assembly is wired to the control panel for the balance of pressure between cylinders. There is no fixed mounting and the cylinders can be bolted exactly where needed, as shown in Fig. 12-24.

12-9-1-3 Self-Contained Cylinders. Self-contained cylinders (see Fig. 12-25) are isolated springs, which already contain the amount nitrogen needed for their function and do not need any additional supply of it. Where balanced force is necessary, several cylinders can be connected together with pressure hoses, as shown in Fig. 12-25.

As with all other springs/cylinders, self-contained cylinders should be protected from the contact with any fluids, be it die lubricants, cleaners, water, or any other liquids. For this reason, their retaining pockets should be provided with adequate draining channels. The spring should always be attached to the bottom surface of its retaining pocket with bolts. This precaution not only prevents the cylinder from being swayed aside during the die function; it also does not allow for a gap to retain metal chips, lubricants, grime, and other debris underneath it.

The piston contact surface should be straight and perpendicular to the die surface. Where a slanted contact surface may be used, side loading will result, which may sway the piston aside and eventually ruin it. Same with surfaces containing pockets or screw heads—these may produce an uneven pattern of wear on the piston rod (see Fig. 12-26).

The disadvantage of single, self-contained cylinders is their height: these types of gas springs are always higher than other cylinder types (see Fig. 12-27).

12-9-1-4 Spring Cushions. These are small assemblies of cylinders under a common pressure pad as shown in Fig. 12-28. As these are very powerful devices, such cushions are useful in aiding the press function and can be installed either attached to the ram, or under

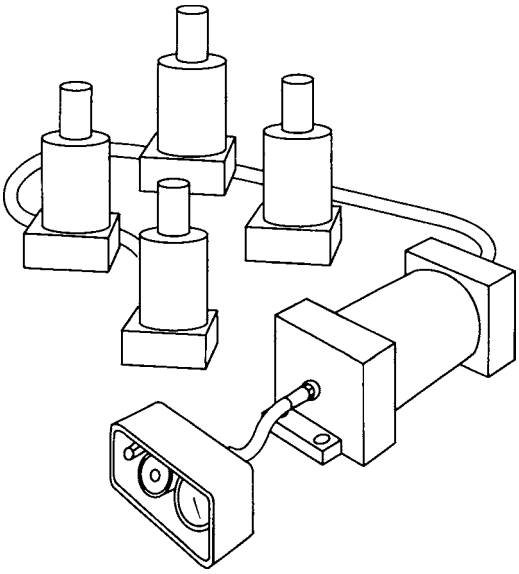

FIGURE 12-24 Hose and tank system. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

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FIGURE 12-25 Super Tanker® Cylinders. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

the bolster, or just about everywhere. The advantage is in their nearly constant force throughout the stroke.

Self-contained pressure pads are also used as cam-driving devices, in which case they can be provided with a cam-driving block or with a roller. Stripper springs for the return pressure must be used in conjunction with the cam pads. The cam-driving cushions also serve well in delayed piercing.

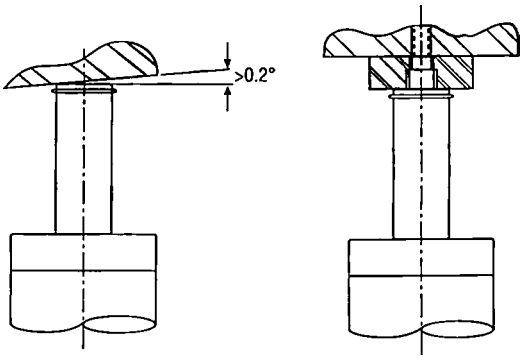

FIGURE 12-26 Inclined or uneven surface produces damage to the piston rod. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

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SPRINGS, THEIR DESIGN AND CALCULATIONS

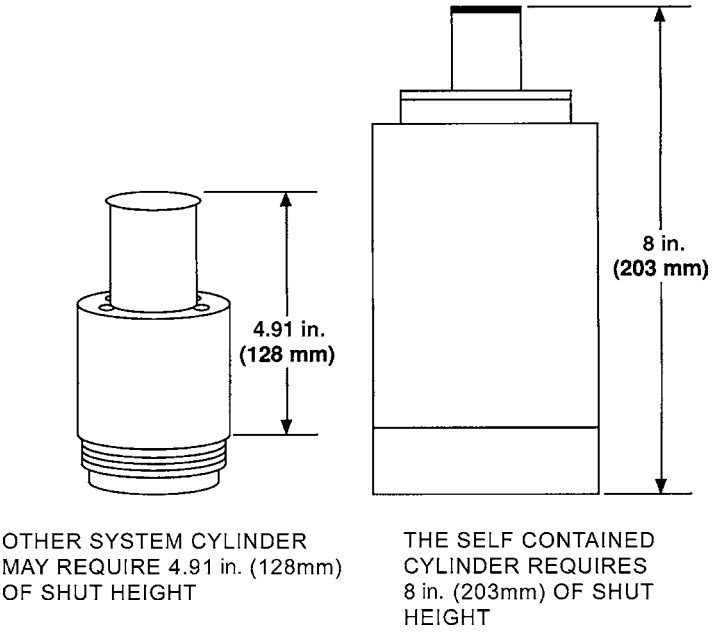
4.91 in.
(128 mm)
8 in.
(203 mm)
OTHER SYSTEM CYLINDER MAY REQUIRE 4.91 in. (128mm) OF SHUT HEIGHT
THE SELF CONTAINED CYLINDER REQUIRES 8 in. (203mm) OF SHUT HEIGHT

FIGURE 12-27 Height of cylinders. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

12-9-2 Air and Hydraulic Cylinders

Air springs, also called pneumatic cylinders (or air pistons) are preferred where long press strokes and adjustable forces of their application are required. Often, these types of springs contain a hollow cylinder, which at the same time acts as a surge tanks for air. The pistons operate on shop air, the pressure of which can be increased at the die closure by implementing one-way check lines at the air inlet.

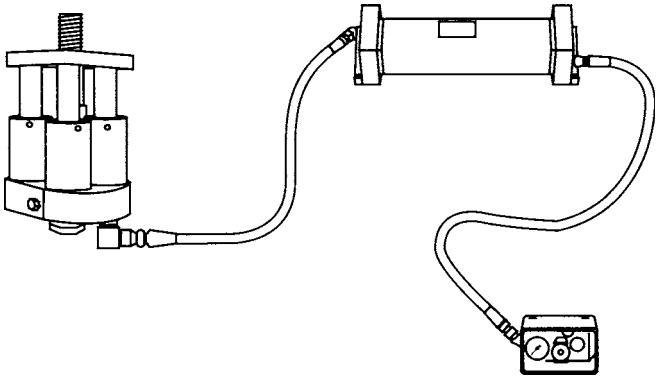

FIGURE 12-28 Spring cushion. (*Reprinted with permission from Hyson™ Products, Brecksville, OH.*)

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Hydraulic cylinders are slower in response, for which reason they are not used in dies too often. However, their usage with some forming applications brings about definitive advantages. First of all, by adding an accumulator of fluid, their force can be adjustable. A press operator can monitor this force by himself or herself and change it on demand, either up or down. Additionally, a typical lifetime of a hydraulic cylinder system is up to 2.5 million cycles, with dependence on other variables, such as the severity of manufacturing operation.

12-9-3 Calculation of Resistant Tonnage for Nitrogen Springs

The tonnage, also called the resistant tonnage, is an important element in the selection of proper nitrogen springs. Resistant tonnage is the force needed to maintain the given pad pressure.

The calculation of tonnage, meaning any tonnage at all, is mostly an open guess and subject to variations due to friction, heat, galling, to name but few invasive effects on the metal stamping field that do not hesitate to exert their influence when the least appropriate.

The resistant tonnage calculation of nitrogen springs is probably bound to change over time, as new formulas come up quickly and the old ones do not die easily. But the basic formula for the drawing tonnage is similar to the calculation of the blanking or piercing pressure, and it can be calculated as follows:

$$V_{TON} = L \cdot t \cdot c \cdot F_s \tag{12-49}$$

where L = length of the line, linear
t = material thickness
F_S = safety factor, 1.2 to 1.25 (i.e., 20 to 25%)
c = coefficient, per values below

The values of the above coefficient c are approximately

23 = for cold rolled steel
18–20 = for aluminum
28–35 = for stainless steel

12-9-4 Comparison of Different Types of Springs

Each of the spring systems described earlier has its advantages and disadvantages. For example, coil springs may still be needed in great quantities for shorter die runs, or where the life of a spring is of no concern. The cost of wound springs is low and their exchange is most often quick and cost-efficient, when not counting the time a die needs for its removal from the press.

Air, gas, and pneumatic springs' performance suffers where a short stroke, high-speed application with many million of cycles are expected. At the same time, longer spring travels with high speed applications can incredibly weaken wound springs.

A nitrogen cushion does not require a compressor; an air spring does need one. The nitrogen spring cushion may cost half of the air cushion's price tag. The force exerted by nitrogen cushion is constant, unwavering. An air cushion's force varies, since the build up of pressure is controlled by the air valves, expansion tanks, and compressors, all attached to the spring. The cost of maintenance for the nitrogen spring is also lower.

If the parts do not come out from the die as they should and a wrong amount of spring force is suspected, it is quite a task to determine the spring pressure received from wound springs. Where an increase in force is needed, wound spring's pressure cannot be easily adjusted.

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SPRINGS, THEIR DESIGN AND CALCULATIONS

Nitrogen gas is nontoxic, colorless, odorless, and inert. It will not ignite under high pressures or in the close proximity of an open flame. Nitrogen gas additionally does not support combustion. Air and other gases may be flammable in some environments. For this reason, their application with dies producing heat, should be limited. Their maximum operating temperature is approximately 170°F, and unless the heat-producing dies are cooled, coil springs should be opted for.

Hose-and-tank system of nitrogen springs is more costly, but it allows for controlling and adjusting the spring pad balance. Their safety factor is greater than that of other spring types.

As seen earlier, each type of a spring has its application range and subsequently, its usage. The proper decision depends on each particular situation, on the die function, and on the environment where it operates. Naturally, the cost factor exerts its influence here as well.

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CHAPTER 13
SPRING WASHERS

Spring washers, even though small in size, may sometimes outperform much larger springs. They are used in offset situations, to provide tension in bolted assemblies, or to furnish the recoil action of springs. Even though their span of deflection is limited because of their size and especially because of their height, a somewhat improved performance may be expected where coupling several washers together. Their stackability, along with their compactibility and versatility, makes spring washers quite advantageous where used in confined spaces or where a stabilizing function is needed.

In bolted assemblies, spring washers are capable of keeping all parts under tension, preventing threaded items from rotating and loosening up. Spring washers can negate the effects of vibration, they can diminish the side-acting force and control the pressure in vibration mounts, aside from many other applications, where their usage is often taken for granted.

Basically, there are three types of spring washers:

- Cylindrically curved washers
- Wave washers
- Conical disks, or Belleville washers

These three basic variations are capable of covering a wide range of loading applications. Where cylindrically curved washers will sustain a loading of several ounces, the sturdiness of Belleville washers allows for loads ranging within tons (Table 13-1).

The effect of loading force is localized in spring washers, which causes a stress response within a small area surrounding the inside diameter of the part. The subsequent deformation tends to increase the affected area in size, which can never be large enough to influence the height of the washer.

Conical washers can take up to 200,000 lb/in.^{2} loading, which is the value of their maximum stress in load cycles of 500,000. With more cycles, loading limits must be reassessed on the basis of fatigue testing of actual washers. However, some conical washers will tolerate stresses in the range of two or three times the maximum permissible value.

All spring washers are usually made of spring steel, with some marginal use of spring brass, beryllium copper, phosphor bronze, and other materials. Hardness of the material does not influence the spring rate of the washer in any way as some may have believed. Corrosion resistance is ensured by application of coatings, which may include electrogal-plating, electro-plating cadmium plating, black oxide, nickel and chromium plating, etc.

The actual usefulness of each washer varies along with its shape, making each of them restricted in application to specific situations, with their interchangeability outright impossible.

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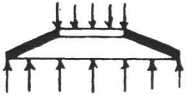
TABLE 13-1 Characteristics of Three Basic Types of Spring Washers

Type	Load capacity	Spring characteristics	Nature of spring contact	Expansion under load	Maximum deflection
Cylindrically curved washers	Light loads Ounces to a hundred pounds	Spring rate approximately linear over entire deflection range	 4 Contact points (2 top, in line — 2 bottom)	Has most expansion of three basic types	1/2 of outside diameter
Wave washers	Light to medium loads Pounds to hundreds of pounds	Spring rate approximately linear, except near flat position	 Number of contact points equals twice the number of waves	Has less expansion than cylindrically curved washers	Approximately 1/4 of outside diameter
Belleville washers	Medium to heavy loads Tens of pounds to tons	Can have: (1) Approximately linear spring rate (2) Increasing spring rate (3) Decreasing spring rate (4) Zero spring rate Load capacity is erratic near the flat position	 Contact around inner and outer circumferences	Has least expansion of three basic types	(Belleville Criterion) 1/10 of rim width

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13-1 CYLINDRICALLY CURVED WASHERS

This type of washer demonstrates a considerable uniformity of spring constant over a wide range of deflections. Cylindrically curved washers are suitable for application of light loads or where repeated cycling with varied range of motion is involved. The recommended range of their maximum height is limited to less than one-half of their outer diameter. Cylindrically curved washers (Fig. 13-1) may be used where tightening of assemblies is needed, to protect them from looseness and lack of stability.

The functionability of these washers should not be hampered by installing them in restricted or confined spaces, as they need room for diametral expansion under loads. The condition and hardness of their bearing surface is of importance as well, since it must allow for easy sliding of edges during expansion, with no subsequent digging into the material.

To calculate the values of cylindrical washers, the following formulas may be used:

$$P = \frac{4Ef\,bt^3}{D^3K} \tag{13-1}$$

where P = applied load, lb
E = modulus of elasticity, lb/in.^{2}
K = empirical stress-correction factor per Fig. 13-2
D = outside diameter, in
f = deflection, in
b = radial width of the material, or $(D - d)/2$
t = material thickness

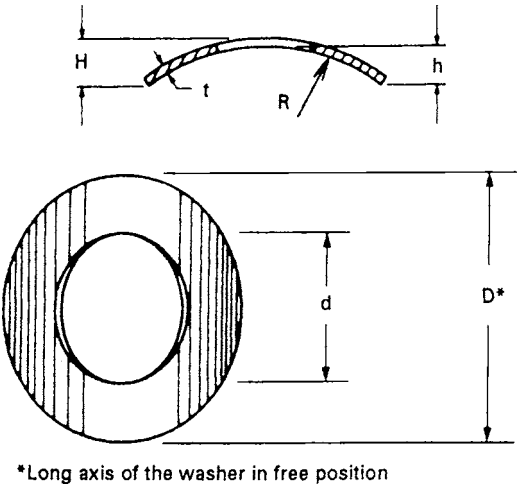

FIGURE 13-1 Typical curved spring washer. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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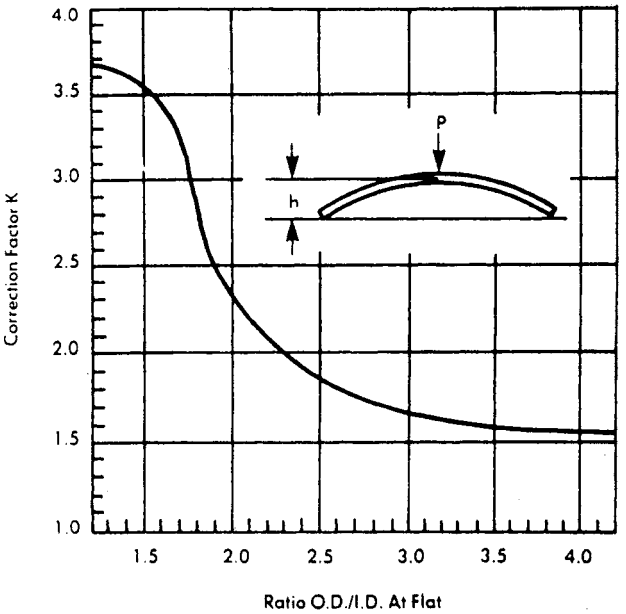

FIGURE 13-2 Empirical stress-correction factor K for cylindrically curved spring washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

The maximum induced stress S will be

$$S = \frac{6Eft}{D^2} \tag{13-2a}$$

or

$$S = \frac{1.5P}{t^2} K \tag{13-2b}$$

where K = empirical correction factor per Fig. 13-2

These equations are valid for deflections of up to 80 percent of the washer's height h, where the actual amount of deflection f is smaller than $1/3D$. Beyond these ranges, the spring rate, which so far was found linear, will begin to rise in value, becoming higher than calculated.

The radius of curvature R may be figured as follows:

$$R = \frac{(D/2)^2 + h^2}{2h} \tag{13-3}$$

Equation (13-3) may be used to evaluate the height of the washer h,

$$h = R - \sqrt{R^2 - (D/2)^2} \tag{13-4a}$$

or the outside diameter

$$D = 2\sqrt{2hR - h^2} \tag{13-4b}$$

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Spring rate k may be obtained from the formula

$$k = \frac{P}{f} = \frac{41.75Ebt^3}{\left(\frac{D+d}{2}\right)^3} \tag{13-5a}$$

where b = radial width of the material, or $(D - d)/2$
k = spring rate, lb/in

13-2 WAVE WASHERS

Wave washers may be used for small to moderate static loads, ranging from a few pounds up to hundreds. They are an excellent choice for mounting within tight or restrained areas, as their outside diameter increases in size only very slightly under a load (Fig. 13-3).

Wave washers are often utilized in situations where some amount of cushioning is required, to offset components of shaft assemblies, or to prevent loosening of parts due to vibration. These washers may be obtained in a wide range of sizes, but for the best balance between their flexibility and load-carrying capacity, the ratio of mean diameter D_m to the radial width of the washer material b should be kept at the numerical value of 8, or

$$\frac{D_m}{b} = 8$$

Ratios smaller than 8 generate a discrepancy between the calculated and actual values of load and stress. Such an impediment to the washer's performance is caused by the inability of waves to assume their previous shape after deflection. Where the D_m/b ratio should fall considerably below 8, a replacement with a Belleville washer is recommended.

The number of waves must be three or more, with the most commonly used washers having three, four, or six waves. By increasing the number of waves, the washer's thickness may need to be reduced for a required load, with a subsequent decrease in allowable

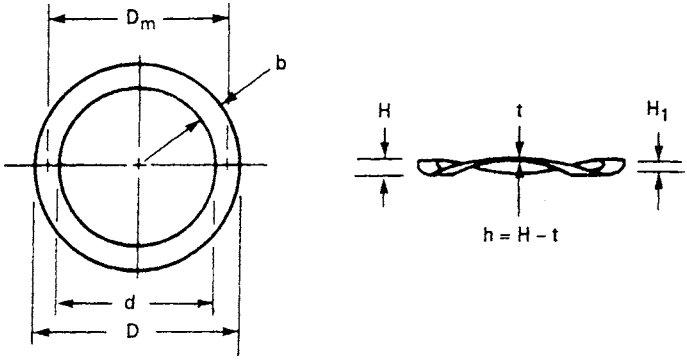

FIGURE 13-3 Typical wave spring washer. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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deflection. The number of waves is based on the desirable spring rate and may be calculated by using the formula

$$k = \frac{P}{f} = \frac{Ebt^3 N_a^4 D}{2.40 D_m^3 d} \tag{13-5b}$$

Dimensional uniformity of waves is important, as the actual load deflection rate takes effect only after all waves are equally loaded. For this reason, the load deflection rate should always be verified against the initial preload. With evenly loaded waves, the spring constant is expressed by a linear segment, especially within the range of 20 to 80 percent of the total available deflection of the washer. The point at which the spring rate begins to deviate from its linear representation differs with various types of washers. Its occurrence should be prevented by making the washer height equal to twice the amount of deflection.

Stress range of wave washers (Table 13-2) may be calculated as follows:

$$S = \frac{0.75\pi P(D+d)}{N_a^2 t^2 b} \tag{13-6a}$$

or

$$S = \frac{\left(\frac{48E}{\pi^2}\right) tf N_a^2}{(D+d)^2} \tag{13-6b}$$

where N_a = number of waves

Material thickness t may be related to the following values:

$$t = \frac{0.635(D+d)(P/bf)^{1/3}}{E^{1/3} N_a^{4/3}} \tag{13-7}$$

where E = modulus of elasticity, lb/in.^{2}
P = applied load, lb
b = radial width of material, or $(D - d)/2$
f = deflection, in

TABLE 13-2 Maximum Recommended Operating Stress Levels for Cylindrically Curved and Wave Washers Made of Steel in Cyclic Applications

	Percent of tensile strength
Life (cycles)	Maximum stress
10^4	80
10^5	53
10^6	50

This information is based on the following conditions: ambient environment, free from sharp bends, burrs, and other stress concentrations, AISI 1075.

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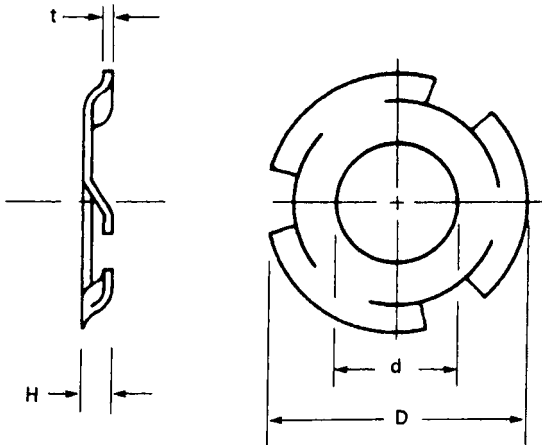

FIGURE 13-4 Typical finger spring washer. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

and the deflection f is tied to a formula

$$f = \frac{\pi^2 S(D+d)^2}{48EtN_a^2} \tag{13-8}$$

13-2-1 Finger Washers

Finger washers are used in static load cases such as those exerted by ball-bearing races. In such an application finger washers are utilized to reduce vibration and noise. Cyclic loading is not recommended for this type of spring washer (Fig. 13-4).

Finger washers combine the equality of distribution of loading of wave washers with the flexibility of curved washers. Stresses, deflection, and other calculations for this type of washer should be calculated considering fingers to be cantilever springs. Actual samples of the calculated values should be produced and tested prior to use.

Finger washers usually do not retain any favorable residual stresses, and they are usually supplied in their stress-relieved condition. Operating stresses from Tables 13-3 and 13-4 may be used for finger washers as well.

TABLE 13-3 Maximum Recommended Operating Stress Levels for Special Spring Washers in Static Applications

Material	Percent of tensile strength	
	Stress-relieved	With favorable residual stresses
Steels, alloy steels	80	100
Nonferrous alloys and austenitic steel		80

*Finger washers are not generally supplied with favorable residual stresses.

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TABLE 13-4 Load Tolerances for Special Spring Washers

Washer type	Stock thickness		± Load percentage
	in	mm	
Curved	0.004–0.039	0.1–1.0	15
Wave	0.004–0.010	0.1–0.25	33
	0.010–0.012	0.25–0.30	25
	0.012–0.020	0.3–0.5	20
	0.020–0.039	0.5–1.0	15
	0.039–0.079	1.0–2.0	12

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13-3 BELLEVILLE SPRING WASHERS

Belleville washers were patented in France by Julien F. Belleville of Paris in 1867. Their use throughout the industry is widespread until this day, because they possess certain qualities not obtainable with any other spring washers.

Being basically coned disk spring washers, the uses of Belleville washers in packing seals, lathes, and clutches are justified by their ability to maintain a constant force regardless of their dimensional variation caused by wear (Fig. 13-5).

Belleville washers' performance is height-sensitive, and with higher cones, there is no increase in spring action, as some may have thought. An increase in height may actually cause an incomplete recovery after deflection, leading to a permanent set of the washer, which may give rise to internal strains, with a subsequent failure of the part.

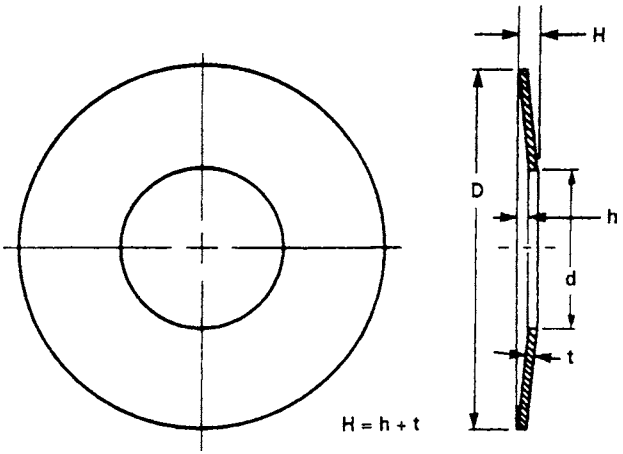

FIGURE 13-5 Belleville spring washer. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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Belleville washers may be produced teethed around both their upper and lower edge. Such teeth may prevent the washer from succumbing to any lateral shifting while not really altering its characteristics.

13-3-1 Design Guidelines

The rules governing the design of Belleville spring washers amount to several basic requirements, established originally by Julien Belleville, which are as listed below:

- The washer's height to the width of its rim should not exceed 1:10 ratio. A relationship exceeding 1:10 ratio results in a maximum recommended angle of cone equivalent to 5.5°.
- Material thickness should be related to the width of a rim at the ratio of 1:5. This ratio should never exceed 1:10.
- Where the outside diameter is equivalent to roughly twice the inside diameter value, the maximum flexibility is attained. Such a relationship also provides the best ratio of the washer's spring properties to its weight.
- With the ratio of OD/ID = 1.5 to 1.7, both the load and stiffness capacities are at their highest regardless of the value of t/h, or thickness to height ratio.
- Formulas used for a washer which is deflected beyond 90 percent of its initial height become inaccurate, with the actual load greater than the calculated value. For the best results, the washer should be designed to arrive at the predetermined load sooner than becoming totally flattened.
- In screw or bolt assemblies, the load supported with a practically flattened washer should be equal to 50 percent of the screw's or bolt's tensile strength.

13-3-2 Height to Thickness Ratio

Load-deflection curves of Belleville washers for various height to thickness ratios are as shown in the graph in Fig. 13-6. It may be observed that a curve for low h/t values turns into almost a straight line. At $h/t = 1.41$, this curve becomes fixed in its value, with dependence on the amount of loading. Such a range lasts for approximately 50 percent of deflection preceding the flat stage, with up to 50 percent of deflection past the flat stage.

With h/t values exceeding the 1.41 range, the load-carrying capacity rapidly diminishes after reaching its peak value, whereas with h/t greater than 2.83, which is exceeding its flattened condition, the washer will snap backward and a force will have to be applied to return it to its original shape.

Belleville spring washers are quite unique in their function, as their stiffness may change over the range of deflection, while the deflection itself may be altered by changing the ratio of free height to thickness, or h/t. A comparison of h/t ratios and their characteristics and applications is given in Table 13-5.

A conical washer of h/t greater than 0.4, when exposed to the maximum loading condition, will show an almost uniform spring constant, which would be maintained up to $h/t = 0.8$. Where the h/t ratio exceeds the 1.41 value, the washer's capacity to support a maximum load will reach its peak and decrease with additional deflection, increasing again once the flattened position is passed. With cessation of the pressure the washer snaps back into its original position.

Where the h/t ratio exceeds the value of 2.8, the load becomes negative if the deflection is pursued beyond the washer's flattened position. Under a continuous application of load

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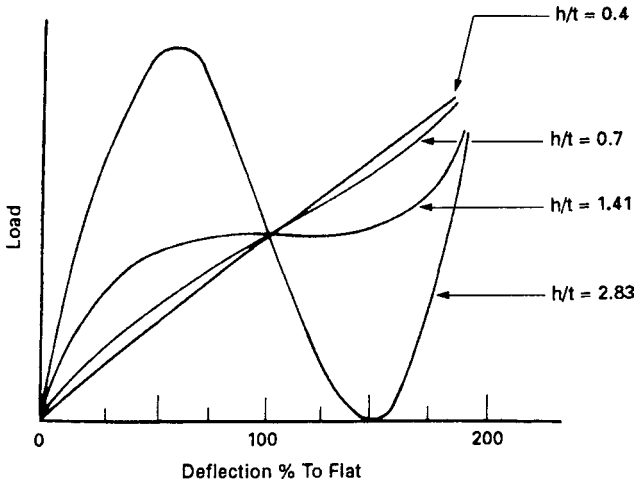

FIGURE 13-6 Load-deflection curves for Belleville washers with various h/t ratios. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

TABLE 13-5 Applications and Load-Deflection Characteristics of Conical Spring Washers Having Various h/t Ratios

Characteristics	h/t ratios	Applications
Constant spring rate	$h/t < 0.4$	Where constant spring rate is required or to obtain very high loads with small deflections
Approximately constant spring rate (Belleville's rules apply)	$h/t < 0.8$	Fasteners and in stacks where approximate linear spring rate is acceptable
Positive, decreasing spring rate	$A < h/t > 1.41$	Fasteners and in stacks. Higher h/t values may cause snapping if deflection proceeds past flat position ($A = D/d$, see Fig. 13-23)
Zero-rate condition over large deflection	$h/t = 1.5$	To take up wear while establishing constant load. To apply gasket pressure and to provide constant pressure in special brakes
Positive, decreasing spring rate which becomes zero, then negative before the flat position is reached	$1.4 < h/t > 2.83$	Special purpose: for fasteners not generally loaded to the flat position, and in devices where an "oilcan" characteristic is desired
Same as above, except the spring washer can remain stable on either side of the flat position	$h/t > 2.83$	Special purpose: in devices where load is required in opposite direction to restore to working position

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the washer becomes inverted, turning inside out, in which position it remains until a load applied from the opposite direction returns it to its original shape and position. This is an effect similar to that of an oilcan, which may be forced to snap out but, unless a force is applied from another direction, never snaps back by itself.

Where $h/t = 1.5$, such a condition is called zero rate, or constant-load condition, and it spans over a large range of deflection possibilities. Such washers are useful in certain types of disk brakes, where they apply the braking pressure to a disk. The conical washer in such an arrangement maintains constant pressure on the disk even as the brake lining wears out because of friction.

Not all applications of Belleville washers require their total flattening under a load. However, these washers should always be designed to withstand an accidental flattening without succumbing to permanent deformation. Where greater loads and deflections are required, several conical washers should be used in such applications, stacked in various arrangements, as shown later in Fig. 13-16.

13-3-3 Mounting of Belleville Washers

The method of mounting of Belleville washers will certainly influence the amount of their deflection and also their performance in service. Where a washer should be mounted on a flat plate, its useful range of deflection will amount to 15 to 85 percent of its height. All deflection rates exceeding 85 percent of height result in higher than calculated loads.

In situations where a Belleville washer is expected to deliver precise loads at the moment its shape is nearing the flattened position, such a washer should be prevented from reversing by banking on a positive stop. Loading in such a case should be applied uniformly over the whole circumference of the washer. The spring rate increases with the deflection beyond the washer's flat position. An applicable method of mounting is shown in Fig. 13-7.

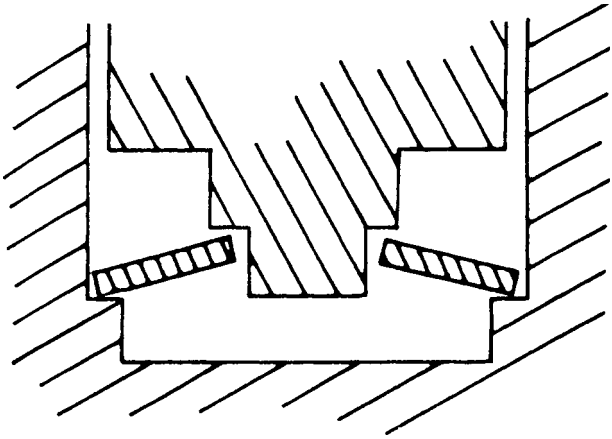

FIGURE 13-7 Mounting of a Belleville washer for deflection past the flat position. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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13-3-4 Stress and Cyclic Loading

Belleville washers should be designed for low stress ranges to prevent their setting when accidentally compressed flat. However, various stresses are not uniformly dispersed over the washers' surface, as they accumulate at different points of their cross section (Figs. 13-8 and 13-9). The highest compressive stress can be found around the top inner edge of the washer. Tensile stresses are the highest around the bottom corners. Stress S_{T2} usually exceeds that of S_{T1} in situations where the h/t ratio exceeds the value of 0.6.

Where cyclic loading is expected, both types of these stresses should be calculated. The washer should be designed with stresses of such a low value as to prevent its setting when accidentally compressed flat. Applicable calculations for such an assessment are presented next.

$$P = \frac{Ef}{MR^2(1-\mu^2)}\left[t^3 + t\left(h - \frac{f}{2}\right)(h-f)\right] \tag{13-9}$$

and

$$S = \frac{Ef}{MR^2(1-\mu^2)}\left[C_1\left(h - \frac{f}{2}\right) + C_2 t\right] \tag{13-10}$$

Equation (13-10) may be adjusted to give the height h as

$$h = \frac{SMR^2(1-\mu^2)}{C_1 Ef} + \frac{f}{2} - \frac{C_2 t}{C_1} \tag{13-11}$$

where M = constant [see Fig. 13-10 or Eq. (13-12)]
C_1 and C_2 = compressive stress constants from Fig. 13-10 or Eqs. (13-13) and (13-14)
$R = D/2$
S = maximum compressive stress at the circumference, ID convex corner
P = applicable load, lb
f = deflection, in
h = inside height, or $H - t$
H = height, overall
t = material thickness
μ = Poisson's ratio

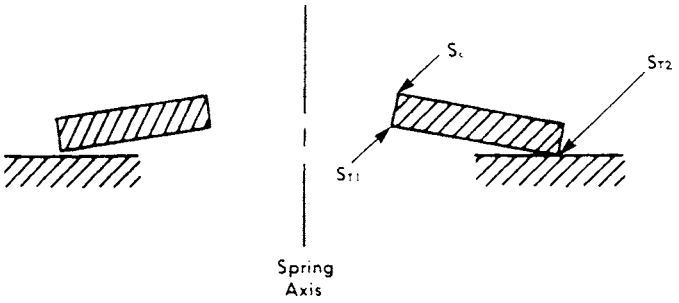

FIGURE 13-8 Highest stressed regions in Belleville washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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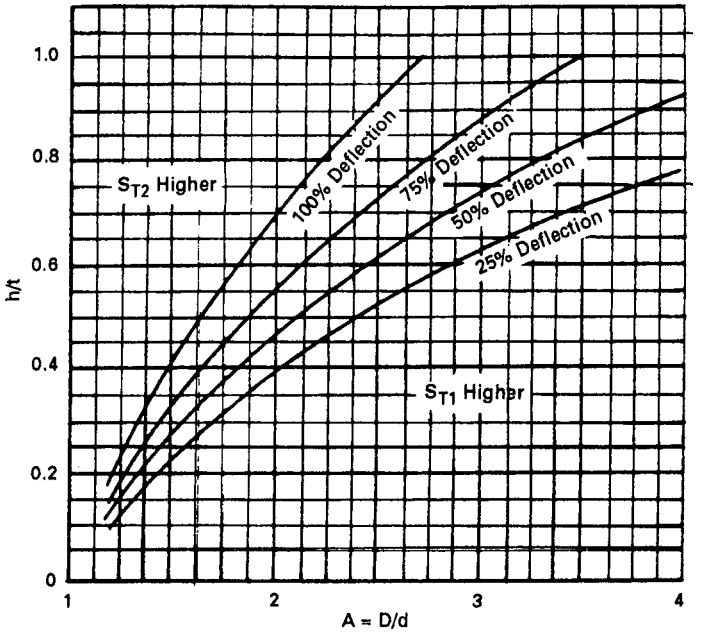

FIGURE 13-9 Comparison of S_{T1} and S_{T2} for various deflections, h/t ratios, and diameter ratios ($A = D/d$) of Belleville washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

$$M = \frac{6}{\pi \ln A}\frac{(A-1)^2}{A^2} \tag{13-12}$$

$$C_1 = \frac{6}{\pi \ln A}\left(\frac{A-1}{\ln A} - 1\right) \tag{13-13}$$

$$C_2 = \frac{6}{\pi \ln A}\frac{A-1}{2} \tag{13-14}$$

Other applicable values may be obtained by using the formulas

$$S_c = \frac{-Ef}{MR^2(1-\mu^2)}\left[C_1\left(h - \frac{f}{2}\right) + C_2 t\right] \tag{13-15}$$

$$S_{T1} = \frac{Ef}{MR^2(1-\mu^2)}\left[C_1\left(h - \frac{f}{2}\right) - C_2 t\right] \tag{13-16}$$

$$S_{T2} = \frac{Ef}{R^2(1-\mu^2)}\left[T_1\left(h - \frac{f}{2}\right) - T_2 t\right] \tag{13-17}$$

where S_c = compressive stress at the convex ID corner
S_{T1} = tensile stress at the concave ID corner
S_{T2} = tensile stress at the concave OD corner

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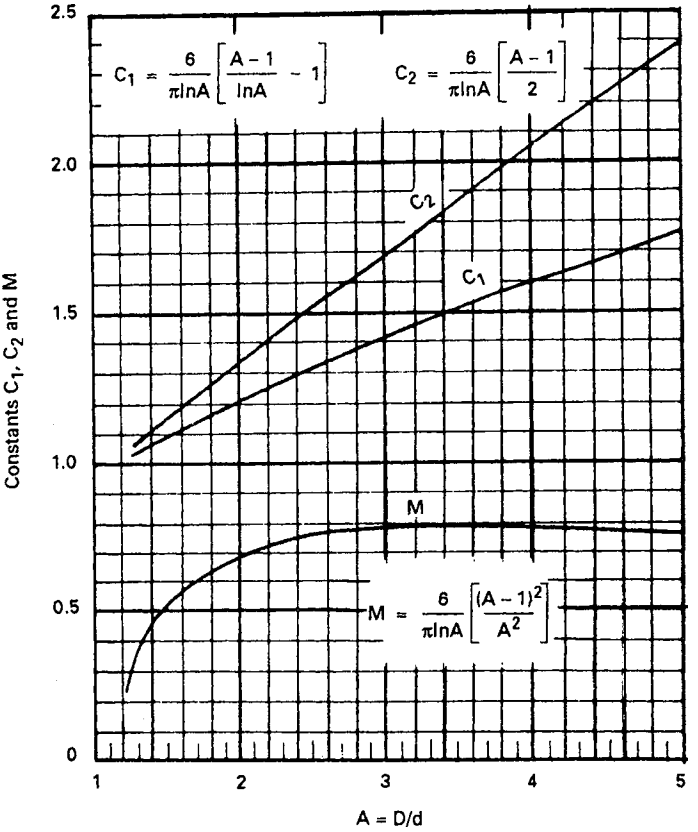

FIGURE 13-10 Compressive stress constants for Belleville washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

T_1 = tensile stress constant from Fig. 13-11
T_2 = tensile stress constant from Fig. 13-11
M = constant from Fig. 13-10
R = ratio $D/2$
A = ratio D/d

With conical spring washers deflected to their flat position where $h = f$, the formulas become

$$P_F = \frac{Eht^3}{MR^2(1-\mu^2)} \tag{13-18}$$

where P_F = load at flat position

and

$$S = \frac{Eh}{MR^2(1-\mu^2)}\left(C_1\frac{h}{2} + C_2 t\right) \tag{13-19}$$

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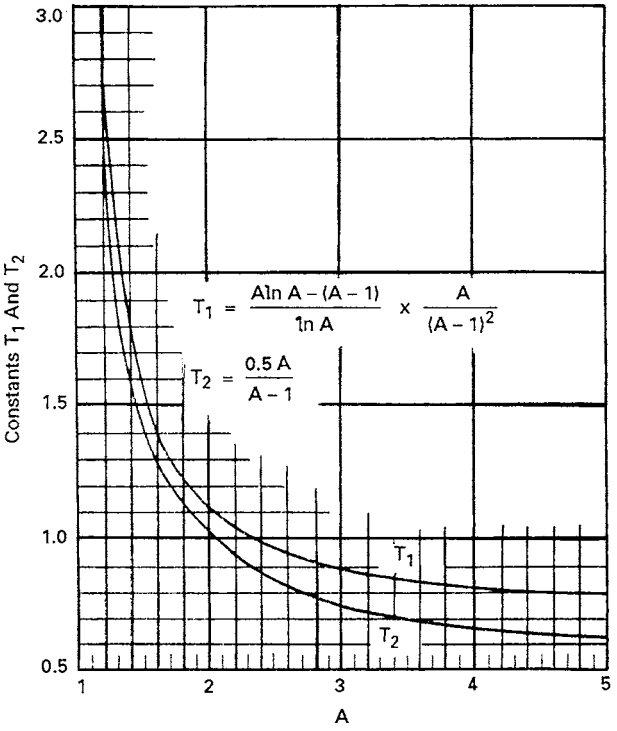

FIGURE 13-11 Tensile stress constants for Belleville washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

All the above scenarios assume a uniform distribution of the load, with the angular deflection of the cross section of the washer almost negligible.

With static loading, the compressive stress S_c acting against the inner convex corner is the controlling element of the set point of a spring. Belleville washers made of carbon steel set when such a stress level reaches 120 percent of their tensile strength. Nonferrous and austenitic stainless steel sets at 95 percent of its tensile strength. With set removed, which is the case with the majority of Belleville washers, compressive stress may reach up to 270 percent of tensile strength in carbon steel washers and up to 160 percent in washers made from nonferrous materials or stainless steel. Stresses can be reduced by increasing the outer diameter or by decreasing the h/t ratio, in which case the graph presented later in Fig. 13-23 may be used. Loads and compressive stresses and load deflection characteristics of Belleville washers are given in Figs. 13-12 and 13-13.

Where cyclic loading is required, both minimum and maximum stress levels and their range at both concave corners S_{T1} and S_{T2} should be evaluated by using a modified Goodman diagram, shown in Fig. 13-14.

The amount of maximum stress delineates the success of all stress formulas. At 500,000 cycles, the typical maximum stress for carbon steel Belleville washers is in the vicinity of 200,000 lb/in.^{2}. However, such a value will change with the type of usage.

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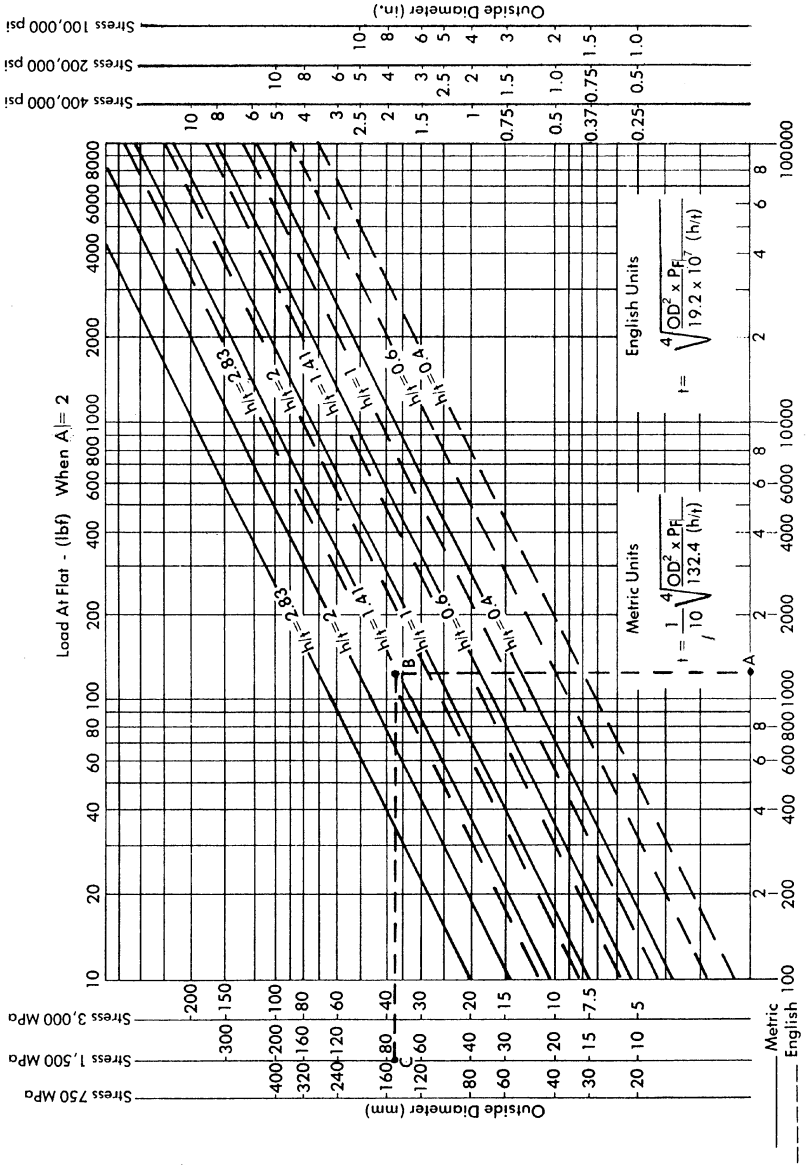

FIGURE 13-12 Loads and compressive stresses S_C for Belleville washers with various outside diameters and h/t ratios. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

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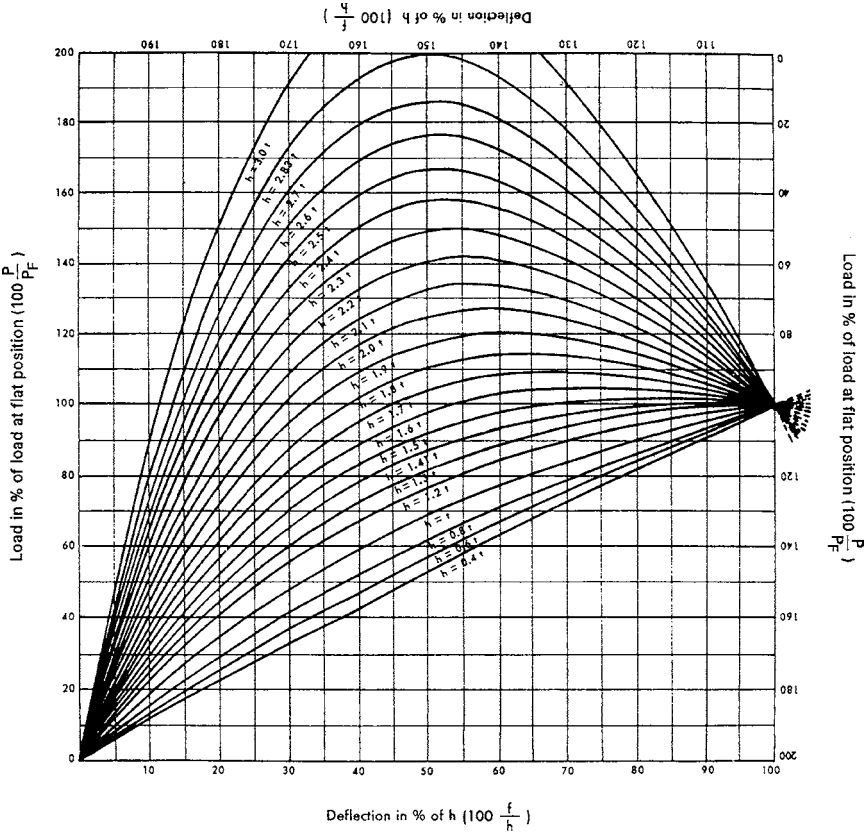
Deflection in % of h (100 f/h)
Load in % of load at flat position (100 P/PF)
Load in % of load at flat position (100 P/PF)
Deflection in % of h (100 f/h)
h = 3.0 t
h = 2.93 t
h = 2.8 t
h = 2.6 t
h = 2.5 t
h = 2.4 t
h = 2.3 t
h = 2.2 t
h = 2.1 t
h = 2.0 t
h = 1.9 t
h = 1.8 t
h = 1.7 t
h = 1.6 t
h = 1.5 t
h = 1.47 t
h = 1.3 t
h = 1.2 t
h = t
h = 0.8 t
h = 0.6 t
h = 0.4 t

FIGURE 13-13 Load deflection characteristics for Belleville washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

13-3-5 Spherically Curved Spring Washers

Instead of cylindrical shapes of Belleville spring washers, segments of spheres may be used. Their characteristics are almost the same as those of conical spring washers, with the exception of the load capacity, which is quite different when nearing the flat position. The shape of spherically curved washers exerts a distinct stiffening influence, resulting in higher spring rates (Fig. 13-15).

The spherical forming radius R_S may be determined by using an equation

$$R_S = R^2 + \sqrt{\frac{(R^2 - r^2 - h^2)^2}{4h^2}} \tag{13-20}$$

where $R = D/2$
$r = d/2$

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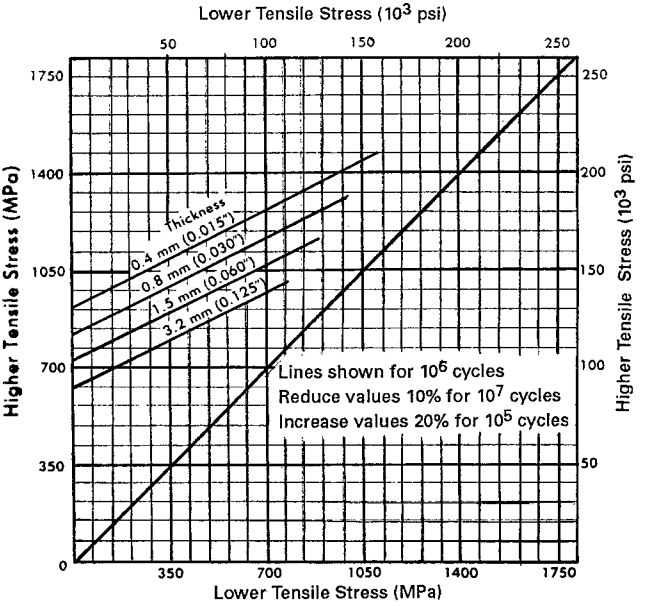

Figure 13-14 may be read as follows:
A belleville washer 0.8 mm (0.030 in.) thick may be expected to have a life of approximately 10^6 cycles when stressed between either

0–820 MPa (0–117,000 psi)
or 350–990 MPa (50,000–141,000 psi)
or 700–1170 MPa (100,000–167,000 psi)

and may be expected to have a life of approximately 10^7 cycles when stressed between either

0–740 MPa (0–105,000 psi)
or 315–890 MPa (45,000–127,000 psi)
or 630–1050 MPa (90,000–150,000 psi)

FIGURE 13-14 Modified Goodman diagram for fatigue strength of Belleville washers. (Carbon and alloy steel at Rockwell hardness 47 to 49 scale C, with set removed but not shot-peened.) (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

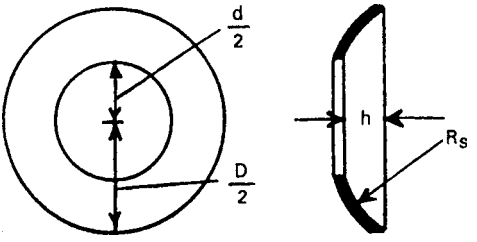

FIGURE 13-15 Spherically curved washer. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

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The same formula may be used for Belleville spring washers whose height equals one-tenth the width of their rim, or

$$h = \frac{R - r}{10}$$

in which case the condition below applies:

$$R_S = R^2 + \sqrt{\frac{(0.99R^2 - 1.01r^2 + 0.02Rr)^2}{0.04(R - r)^2}} \tag{13-21}$$

13-3-6 Multiple Conical Spring Washer Assemblies

Conical washers, when stacked, provide greater deflections, along with larger loading possibilities. Where an indefinite n amount of washers is assembled in series, each washer provides $1/n$-th of the total deflection, while the maximum obtainable load is that of a single washer. Where the h/t ratio exceeds 1.35, such a series of washers will tend to snap back when forced past the flat position.

Loading of a parallel stack of washers is equal to the $1/n$-th load per single washer, multiplied by the number of washers within the assembly. The deflection of the whole stack is equal to the amount of deflection of a single washer (Fig. 13-16).

Hysteresis is greater with parallel-arranged than with series-oriented washers. Its effects may be diminished by proper lubrication (Fig. 13-17).

Where stacks of washers are used, their guidance should be provided by a centrally located pin or tube. Clearance values between these segments should be approximately 1.5 percent of the spring washer inner diameter. Recommended dimensional tolerance values are as shown in Table 13-6.

Stacking of combined parallel and series arrangements provides greater deflections and higher load capacities. Parameters governing assemblies of parallel sets of spring washers arranged in series may be calculated with the aid of the following formulas.

$$P = wP_F \tag{13-22}$$

$$Y_F = mh \tag{13-23}$$

$$L = m(wt + h) \tag{13-24}$$

$$S_T = \frac{wS_{T-F}}{m} \tag{13-25}$$

where P = applied load, lb
P_F = load necessary to flatten the washer, lb
w = number of spring washers in each parallel set
m = number of parallel sets in a series
Y_F = total deflection at flat height, in
S_T = stiffness at deflection f, lb/in.
S_{T-F} = stiffness at flat height, lb/in.

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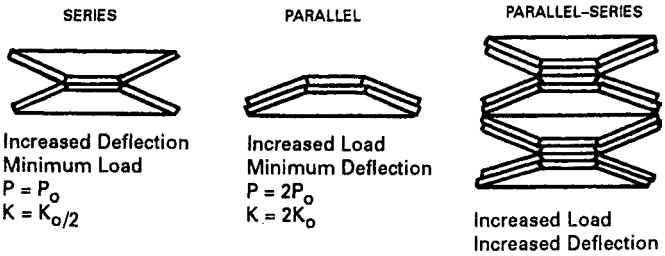

FIGURE 13-16 Load and deflection relationships for conical spring washers stacked in series, parallel, and parallel-series combinations. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

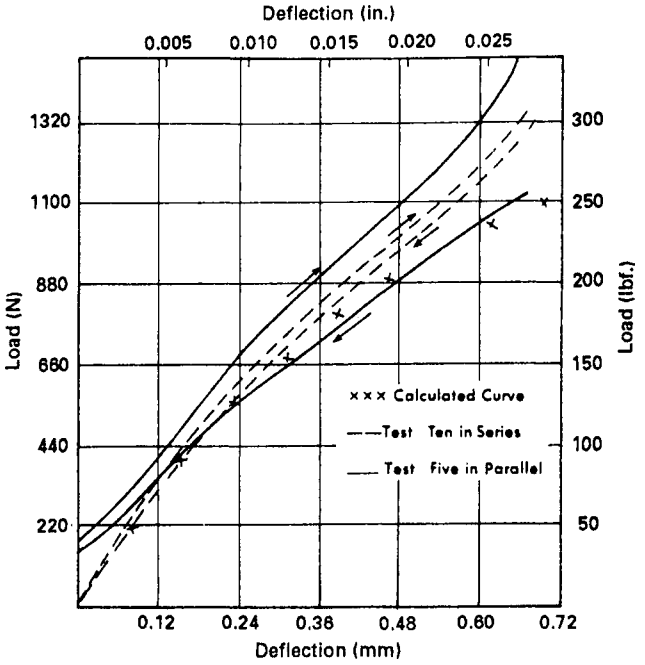

FIGURE 13-17 Hysteresis in stacked Belleville washers. (*From* "Design Handbook," *1987. Reprinted with permission from Associated Spring, Barnes Group, Inc., Dallas, TX.*)

TABLE 13-6 Belleville Washers' Diameter Tolerance

	OD mm (in)	ID mm (in)
Diameter, mm (in)	+ 0.00	–0.00
Up to 5 (0.197)	–0.20 (–0.008)	+0.20 (+0.008)
5–10 (0.197–0.394)	–0.25 (–0.010)	+0.25 (+0.010)
10–25 (0.394–0.984)	–0.30 (–0.012)	+0.30 (+0.012)
25–50 (0.984–1.969)	–0.40 (–0.016)	+0.40 (+0.016)
50–100 (1.969–3.937)	–0.50 (–0.020)	+0.50 (+0.020)

Based on $A = 2$; increased tolerances are required for lower A ratios.

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SPRING WASHERS

13-3-7 Thickness of Washers and Load Tolerances

It may be established from the observation of deflection formulas that the load capacity of spring washers depends on the cubed thickness of the material used. With any change in thickness, a whole array of changes in washer loading may be observed.

To determine the correct material thickness, the following formulas may be used, with their respective values taken off the graph shown in Fig. 13-18.

$$\pm T_t = t\left(\sqrt[3]{1 \pm \frac{P_t}{100}} - 1\right) \tag{13-26}$$

and

$$\pm P_t = 100\left[\left(\pm\frac{T_t}{t} + 1\right)^3 - 1\right] \tag{13-27}$$

where t = material thickness, nominal, in
P_t = load tolerance, percentage of the total load
T_t = thickness tolerance, in

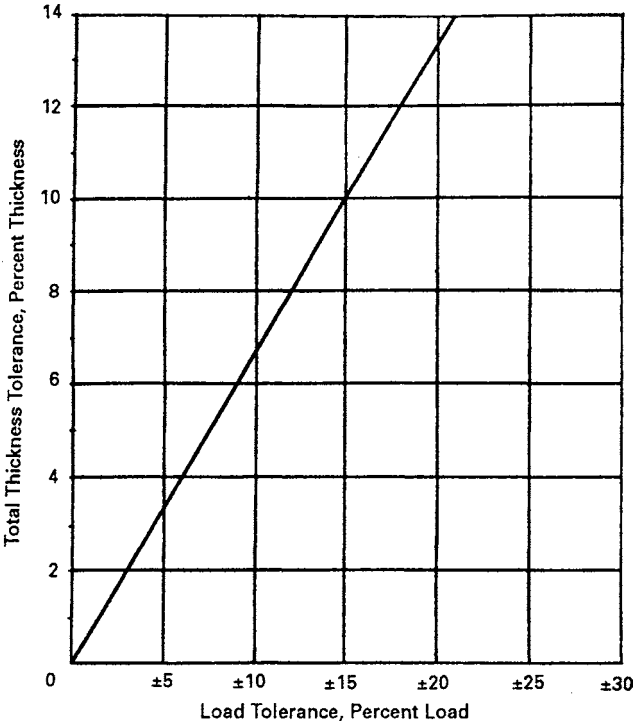

FIGURE 13-18 Graph for use in determining the proper thickness and load tolerances for spring washers. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

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By using the tolerance range in terms of thickness percentage, the graph in Fig. 13-18 may help to assess the variation in load capacity. With demands for tighter load specifications, materials with more accurate thickness tolerances should be used.

Material thickness may also be calculated as follows:

$$t = \sqrt[4]{\frac{D^2 P_F}{19.2 \times 10^7 (h/t)}} \tag{13-28a}$$

The same formula adapted to the metric system will be

$$t_{\text{mm}} = \frac{1}{10} \sqrt[4]{\frac{D^2 P_F}{132.4(h/t)}} \tag{13-28b}$$

where P_F = load necessary to flatten the washer, lb

Basic designs of typical spring washers are shown in Fig. 13-19. The most common cylindrically curved spring washer is shown at *A*. It is capable of providing the greatest quantity of spring action for its size and thickness. The washer shown at *B* is a modification of this design, with an increased load capacity, but at reduced springiness. *A* and *B* styles offer the greatest deflection possibilities, but their load-bearing surfaces are the smallest.

Spring washer *C* banks on two flat portions. It is more rigid than the design shown at *A* and is capable of carrying greater loads at the same material thickness. The conical washer *D* and spherical washer *E* have the best load-carrying capacities when compared to any spring washers of the same size. Their amount of deflection is somewhat smaller, but their springiness is very powerful. A modification of this washer is shown at *F*.

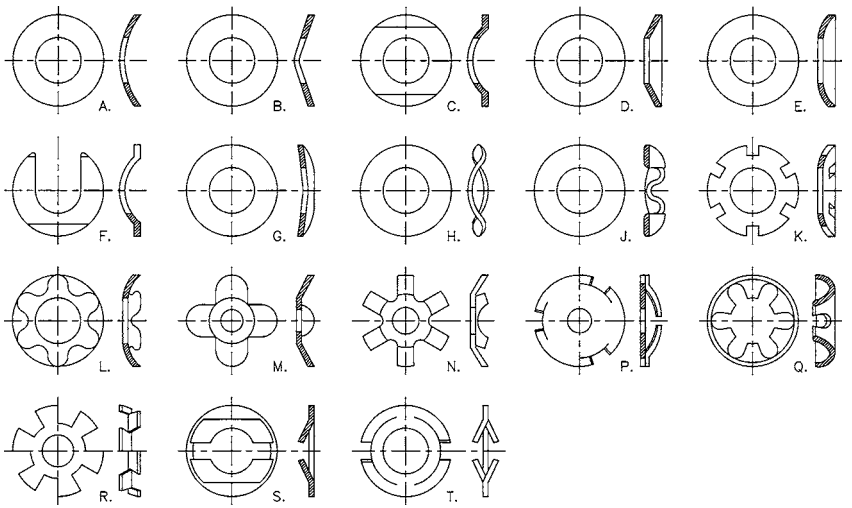

FIGURE 13-19 Basic designs of spring washers.

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The washer shown at *G* has two waves and two contact surfaces, at which it banks in assembly. The *H* washer is a three-wave type, with three contact points per side, and its load-carrying capacity exceeding that of the *A* and *G* types. Multiple waves shown in washer type *J* increase its load-carrying capacity in comparison to the *H* washer. These two washers offer a high spring force, combined with minimum spring movement.

K, L, M, N washers are modified versions of washers *D* and *E*. Decoratively appealing, the scalloping of their circumferences enhances their spring movement, while achieving more uniform distribution of pressure.

Elasticity of fingers, shown at variation *P*, provides for balancing of the applied pressure even at the greater distances off the washer's center. This type of spring washer is often used as a ball-bearing retainer. Washers *Q* and *R* show a difference in arrangement of their teeth, where in designs *S* and *T* these are replaced by fingers.

13-4 LOCK WASHERS

Toothed lock washers display an impressive load-supporting capacity at quite a small overall height. Their teeth, which are always in contact with the material, may enhance their action by digging into it, as shown in Fig. 13-20, type *B*. The type *A* washer in the same illustration may sometimes have its teeth twisted and provided with a stiffening rib, as shown in the lower left-hand view.

The effectiveness of the lock washer's teeth embedding within the material depends on the amount of the washer's coverage, or its blockage by the screw head. Another influence is exerted in the form of the bearing material hardness, which may or may not allow for the washer's penetrating its surface.

Helical lock washers, shown in Fig. 13-21, deflect in installation, keeping the retaining part, usually a screw or a bolt, under a constant tension. Surfaces of these washers are hardened and tempered, providing for greater applicable tightening torques, combined with excellent thrust characteristics.

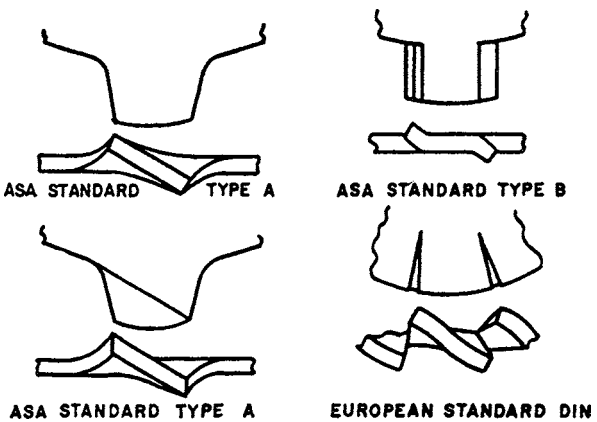

FIGURE 13-20 Toothed lock washers are designed to hold either by spring action or by "digging-in" or by a combination of both. Pictured are four commonly used types. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

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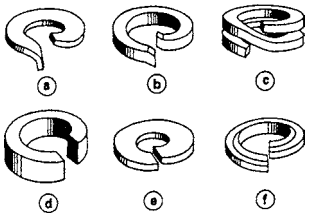

FIGURE 13-21 Helical spring lock washers for special applications: (*a*) wood spring lock washer; (*b*) positive-type washer; (*c*) double-coil type; (*d*) Hy-Collar type; (*e*) wide bearing lock washer; (*f*) ribbed type. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

A cross section of a helical spring washer, shown in Fig. 13-22, shows slanting of the edge surface, with the *A* dimension emerging smaller than *B*. This change in thickness is purposely provided for protection against washers' spreading out and exceeding their diametral size during tightening.

Helical spring washers may be wound on wire-forming machines, in which case their cross section is of trapezoidal shape. However, stamped sheet-metal products are often used as well, with their cross sections either square or rectangular. The free height of the latter parts is usually provided at the range of twice the washer thickness.

Special shapes of helical spring washers, shown in Fig. 13-21, have different usages within the industry. Type *a* washer is recommended for soft bearing surfaces, such as wood, plastic, and the like. Its unrestrained end becomes embedded in the material of bearing surface, preventing any rotation of the washer during tightening. The other end, oriented toward the opposite member of the assembly, is driven into that material, to prevent loosening in service.

The *b* type washer provides a similar service without denting the bearing surface. For greater range of functions, a double-coil washer of the *c* type is recommended. It is used in assemblies, where a combination of wood and metal is utilized.

Washer type *d*, designed for socket head cap screws, is used in confined spaces or with recessed screw heads. The height of this type of collar washer is much greater than that of the next type *e*, the latter being used instead of regular washers in conditions where an additional spring tension is needed. This type of washer is of advantage where

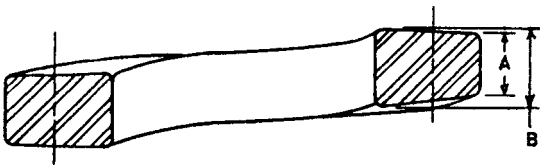

FIGURE 13-22 To prevent worming out, or spreading during tightening, many helical spring lock washers are made so that the peripheral thickness *A* is less than that at the inner surface *B*. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

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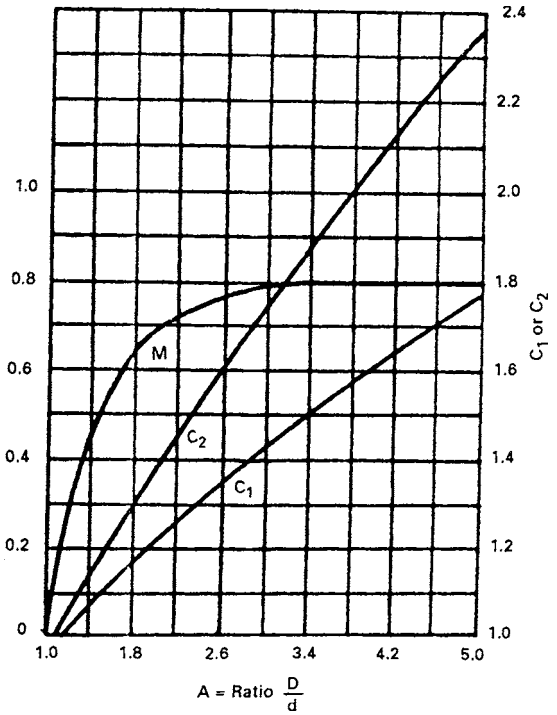

FIGURE 13-23 Graph for determining constants M, C_1, and C_2 employed in the design equations for conical disk washers. (*Reprinted with permission from H. K. Metalcraft Co., Lodi, NJ.*)

an uneven supporting surface is encountered or with larger than necessary clearance holes.

The *f* type of washer contains a rib surrounding its inner periphery. Such a shape, when compressed, engages the thread of the bolt or screw, locking the whole assembly.

Figure 13-23 provides a graph for determining the constants M, C_1, and C_2 used in the design equations for conical disk washers.

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CHAPTER 14
MATERIALS AND SURFACE FINISH

14-1 METAL MATERIALS AND THEIR PROPERTIES

Many designers and engineers wonder on a daily basis if they are using the correct material for a given application or if a better choice could be made, because in the field of material selection the choices are vast and are continuously expanding. New materials are developed whenever the old composition does not meet the industry requirements.

Over the years the industry assembled an impressive inventory of various steels, alloys, and other materials, causing perhaps many to fear that they may not see the forest for the trees. Therefore, the decision to use a particular material for the given application is often based on hours and hours of laborious research and evaluation. And yet an idea may often lurk somewhere, perhaps in our subconscious, that a better, cheaper, more advantageous, and more appropriate selection could have been made.

The already complex problem of material selection is further impaired by the fact that even though so many materials are now available many designers may not be acquainted with them in detail. There is just too much material to be studied, with too many facts to be assessed. One has to have a mind of a computer to be able to store data in bulk and yet exercise some sort of selective control and evaluating properties, which is quite an unlikely combination. Nobody expects the computer to think and nobody should expect a person to store data the way a computer does.

To select a proper material for an existing problem, the material characteristics must be evaluated first. Limiting properties should be surveyed for a proportion of their disadvantage, compared to a practical usefulness. Beneficial aspects should be looked into, if they're not overly beneficial, to actually impair the process they are supposed to enhance. This may happen surprisingly often. For example, a material perfect for its frictional qualities may fail in operations, where only a certain amount of friction is necessary. Or a material of high elastic limits will be detrimental to the cutting process, where it may behave like chewing gum.

Outright harmful attributes should be surveyed as well, to compare their spectrum of influence to the degree of actual usefulness. Some materials are too brittle, but if used where brittleness is needed, they may prove to be an excellent choice. Another material may suffer from excessive spring-back, or lack of it, and its application should be selected to suit such capabilities. As already said, choices are vast and proper selections can become complex and intricate.

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14-1-1 Metallurgy of Metals

The first aspect to be evaluated when searching through the material jungle is the metallurgical process the particular stock has been subjected to, along with the amount and influence of additives it contains.

Metals, when in their annealed form, consist of a mixture of carbon particles, deposited within a base of low-alloyed iron. In such a state, metals are easily machinable and relatively soft. During heat treatment, when subjected to high temperatures in the vicinity of 1400 to 2300°F, the metal is austenitized. Some of its carbon content melts and dissolves in the iron matrix. On cooling down, or quenching in either water, oils, air, or molten salts, a martensitic transformation occurs, producing a hard and brittle substance. The base iron alloy, even though now considerably more alloyed by the addition of dissolved carbon, suffers from residual stresses and is far from being tough enough to function as an element of tooling.

The metal is subjected to another heating cycle, which is called tempering, at temperatures between 300 and 1200°F. Tempering relieves some residual stresses, while precipitating a portion of alloyed elements. Toughness of the material is enhanced, protecting the finished product from the shock of an impact in cutting and similar operations.

14-1-1-1 Rimmed Steel. Rimmed steel is always low-carbon or medium-carbon steel. When poured into the ingot mold, it solidifies quickly around its periphery, which leaves the remaining steel in the middle "shut off" the access to the surface. Without a connection with the outside, gases become entrapped within the mass of an ingot, dispersed in the form of small bubbles. In a solidified ingot, these small bubbles form tiny cavities within the material, disturbing its structure.

The surface of a rimmed product may be perfect, smooth, and of a high finish. But the inner material may be damage-prone, owing to little inner pockets affecting the unity of the material.

14-1-1-2 Killed Steel. Killed steel does not suffer from the emergence of inner gas bubbles, as the solidification process is regulated not to produce them. On solidification, the whole ingot begins to form an indent in the center of its mass alongside its axis, starting from the top. This impression is not of a great depth, but the material from that portion has to be disposed of. Killed steels are usually those containing either higher carbon content or those that are more alloyed. Their surface finish is mostly inferior.

Where rimmed steels do not have a significant amount of silicon (sometimes they have none), the silicon content of killed steels is over 0.15 percent. Silicon aids in deoxidation and degasification of the material.

14-1-2 Fe—C Phase Diagram

The Fe—C or Fe—Fe_3C phase diagram represents the relationship between the iron and carbon within the molten steel material, recording changes in the solidifying mass. These processes, assigned to various temperature ranges and further influenced by the carbon content, influence the structure of material and its reaction to heat treatment during each particular phase (Fig. 14-1).

On solidification, the excess carbon may be segregated in the form of either graphite or iron carbide Fe_3C, also known as *cementite* (containing 6.67 percent C). Iron carbide, when compared to other types of carbon, is very hard, nonductile, and readily affected by stresses within the material.

Ferrite, the α iron, is a ferromagnetic material, quite ductile, with tensile strength under 45,000 lb/in.^{2}. Carbon's solubility within ferrite is very limited, because the cubic structure of ferrite, with oblate spaces among atoms, cannot be modified enough to include even a very small atom of carbon.

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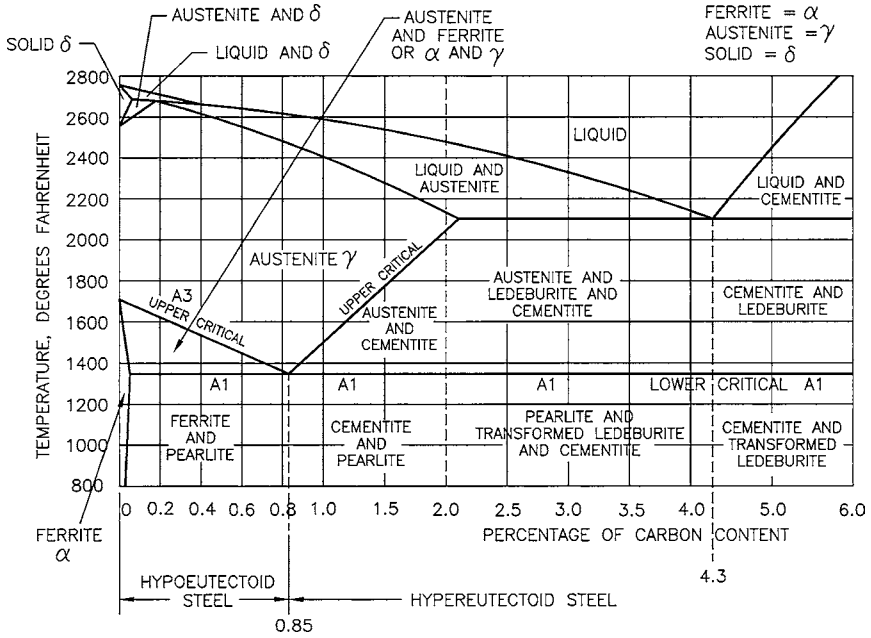

FIGURE 14-1 Fe—C phase diagram.

Ferrite is similar to austenite, or γ iron, even though the latter's atoms are more densely spaced. That's why during the heating cycle, when the transfer from the ferrite phase to austenite takes place, contractions within the material amounting to some 0.29 percent may be encountered. This has a considerable importance in heat treatment, with regard to the development of residual stresses. Austenite is not ferromagnetic.

δ iron, sometimes called δ ferrite, is quite similar to ferrite. It is a solid solution, which means a homogeneous solid mass of a binary or more complex alloy, the chemical composition of which may be altered at a certain range without subsequent modification of its properties. The crystalline lattice of such a solution is the same as that of one of its constituents.

The phase diagram is the basic tool of evaluation of various heat-treating processes for the majority of steels. Their ranges are shown in Fig. 14-2, where their dependence on temperature and carbon content is obvious.

14-1-3 Additive Elements Within the Metal Material

Various metallic and nonmetallic elements, when dissolved within the iron matrix, have the capacity of affecting and altering the qualities of the finished material. Some additives make the metal more brittle, others make it more ductile, and some are still controversial in their effect.

According to the influence of additives on the metal material, they may be divided into three basic groups:

1. Additives detrimental to the material quality
2. Additives beneficial to the material quality
3. Alloying additives

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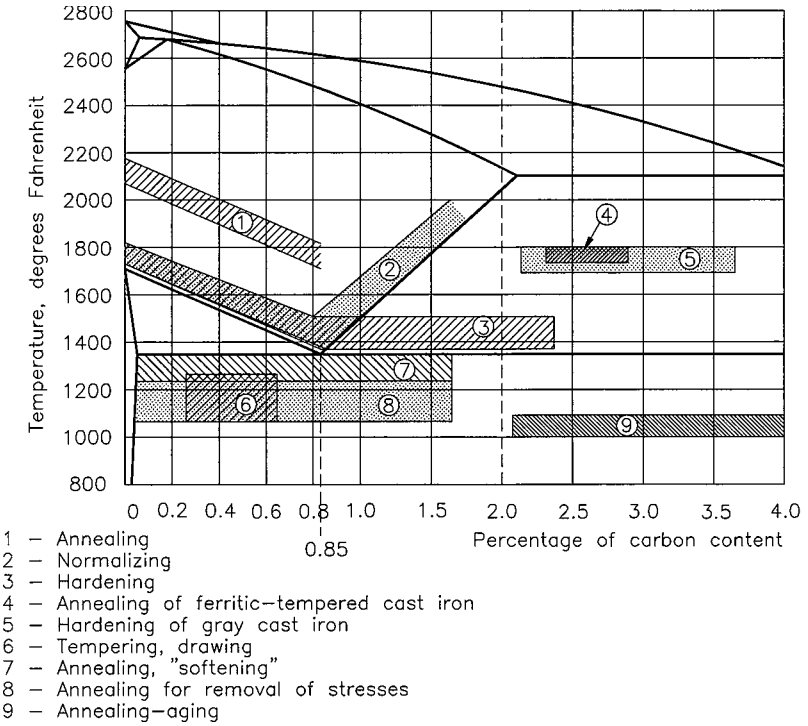

FIGURE 14-2 Fe—C phase diagram. Heat treatment data.

14-1-3-1 Additives Detrimental to the Material. Small quantities of byproducts left from the deoxidating process remain within the metal content in the form of inclusions. These are most often oxides, silicates, aluminates, and sulfates, and they may be of

- Endogenous type, or those produced from within
- Exogenous type, produced from without, due to external causes, such as the melting environment and machinery

Where they are too numerous or unequally distributed, these inclusions affect the mechanical properties of the material, making it less fatigue-resistant and less tough. Oxides and nitrides of aluminum are usually distributed evenly; they improve the grain structure and the drawability of material. However, other inclusions, mostly detrimental to the quality and mechanical properties of steel, are undesirable, and an attempt to remove them or minimize their effect is prevalent. Other harmful elements are hydrogen, nitrogen, oxygen, phosphorus, and sulfur.

Hydrogen (H). This element may become entrapped within the molten mass in the manufacturing process. During the solidification phase, most of the hydrogen evaporates, until only about one-third of the original amount is left within the material. This hydrogen does not remain intact but strives to separate itself from the melt, being attracted by areas of submicroscopic defects, interstitial impurities, vacancies or microvoids, interfaces, or grain boundaries. There, locked in and compressed by the solidifying mass of metal, it is retained under pressure, until the material cracks later under the force. This type of destructive

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behavior is called hydrogen embrittlement. Low-alloy steel with some nickel content is especially susceptible to such a defect.

Hydrogen may be removed from steel by an annealing process, where the material is heated for an adequate time and held at such a temperature until the hydrogen content is diminished. Another manufacturing method of hydrogen prevention rather than removal is vacuum casting.

It is believed, but not yet completely proved, that hydrogen is capable of active interaction with material defects, such as microvoids, grain boundaries or interfaces, dislocations, vacancies, or atoms of impurities of substitutional and interstitial types. A large number of experiments have shown that impurities actually act as hydrogen traps, to which this element is attracted, to form stable, diatomic complexes.

Nitrogen (N). This element is readily dissolved in the molten steel, and its amount depends on the type of manufacturing method. Excessive nitrogen is expelled from the solidifying material in the form of nitride Fe_4N, only if the metal solidification is adequately slow. At speeding up of this process, nitrogen forms a volatile solution within the α steel.

With greater content of nitrogen, the metal is exposed to various changes from within, which produce a decrease in its notch impact strength, ductility, drawability, and formability. Overall, these changes as grouped together are called *aging* of metal. Aging continues to progress at regular temperatures and may be accelerated by heating the metal to some 730 to 900°F. Metals susceptible to aging include "softer" carbon steels, which may fail in service due to this tendency if used in higher-temperature environments, such as welded steel objects or boiler parts.

The lower the amount of nitrogen within the steel, the less affected by aging it becomes. Therefore, the nitrogen should be forced to form temperature-stable nitrides wherever possible.

In some materials, nitrogen is purposely added to the austenite, since it improves and refines the grain structure. In high-chromium steels, nitrogen is an indispensable element in case hardening.

Oxygen (O). Oxygen may become entrapped within the metal mass during the period of oxidation, which depends on a certain amount of it being present within the material. The excess oxygen not utilized by this mechanism cannot simply dissolve itself and evaporate from the metal content, being restricted by the presence of carbon. In the solidified steel, the amount of oxygen may be found at some 0.05 percent.

Oxygen lowers the notch impact strength of the material. It is usually tied to various inclusions, such as oxides (MnO, FeO, Al_2O_3) or silicates (SiO_2). Other deoxidants are aluminum, silicon, and somewhat titanium, zirconium, and calcium.

Phosphorus (P). Dissolvable within the melt γ, phosphorus raises the temperature of the transformation point *A*3 while lowering that of *A*4. The amount of phosphorus within the steel rarely exceeds 0.1 percent. Like sulfur, it separates from the melt during the process of solidification, impairing the solubility of carbon. Its effect on the mechanical properties of steel consists of negatively affecting the notch impact strength, promoting brittleness, and impairing weldability.

Sulfur (S). This element forms a sulfide FeS with iron, which remains insoluble within the solidifying molten mass. Repelled by the solidification mechanism, sulfides migrate to the areas of slowest solidification, which are located at the top of the ingot, concentrated around its central axis.

Sulfides' action consists of their enwrapping the material's austenitic grain structure and impairing its cohesion, which results in an intergranular cracking. They increase the brittleness at higher working temperatures and decrease the toughness, strength, ductility, and machinabity of the material.

Sulfur readily combines with manganese, if the latter is present. It forms MnS at high melting temperature of approximately 3000°F. Most of this sulfide is expelled from the material along with the slag.

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14-1-3-2 Additives Beneficial to the Material. Copper, manganese, and silicon are elements that influence steel positively, enhancing properties that are advantageous in a wide range of applications.

Copper (Cu). This element slows down the recrystallization rate and slightly improves the toughness of the finished material. It usually gets into the metal in the form of an ingredient of various ores or from the metal scrap added to the process. Quantitatively, copper hardly ever exceeds 0.2 percent. Amounts ranging at about 0.1 percent improve the resistance to corrosion, weathering effects, and humidity. Larger amounts of copper are not beneficial at all, as they enhance the tendency of the material surface to crack during heat working.

Manganese (Mn). A deoxidant and sulfur repellant, manganese is used most often in quantities of 0.1 to 0.8 percent within the steel makeup. When dissolved in the ferritic substance of the material, it somewhat increases the toughness and strength of it, while decreasing its brittleness and improving forgeability. A small portion of manganese dissolved in cementite enhances its stability. Eutectoid concentration displays a marked dependency of carbon on manganese content; with increased percentages, the amount of carbon decreases and vice versa. Manganese further lowers the recrystallization speed while lowering the temperature ranges at which this process takes place as well.

However, manganese alone is not an adequate additive for deoxidation of the material, as it is not capable of preventing the reaction of carbon with the solidifying alloy. An unrestricted carbon action produces a material that is not completely killed, which may be detrimental to parts made out of it later under the assumption that it is killed. To aid the process, an inclusion of silicon, a deoxidant, or a combination of silicon and aluminum is necessary. Other deoxidants are titanium, zirconium, and calcium.

Silicon (Si). This is usually added to serve as a deoxidant, in quantities of up to 0.5 percent. It increases the ferritic resistance but lowers the material's formability and machinability, while improving hot-forming properties. All deep-drawing steels must have controlled, low amounts of silicon; otherwise the drawing process will be impaired.

Like manganese, silicon controls the amount of carbon in eutectoid and austenitic steel, making their quantities dependent on its percentage. Silicon further controls the proper dissolving of carbon within the base material, which makes this additive especially useful in the production of cast iron.

Special steels contain up to 1.5 to 2.5 percent silicon, in which case their hardenability, strength, and toughness are enhanced. Silicon, when added in such a large percentage, improves the electrical properties of the material, for which these steels are sometimes called electrical steels.

14-1-3-3 Alloying Additives in Steel Metallurgy. Another group of materials to consider in steelmaking practice are alloying elements.

Aluminum (Al). This element is an excellent deoxidizer, along with other elements such as titanium, zirconium, and calcium. It is also utilized for controlling the grain size.

Cobalt (Co). Cobalt in small amounts supports the hot hardness of alloyed steel. However, in large amounts cobalt is not beneficial, as it reduces the toughness of the material, increases its decarburization tendency, and raises the critical quenching temperature.

Chromium (Cr). This element increases the depth of hardness penetration and the material's response to heat treatment. The usual content is 0.5 to 1.5 percent Cr, with the exception of stainless steels, which contain the amounts of 12 to 25 percent. In stainless steel, chromium is usually paired with nickel, providing the alloy with resistance to corrosion and oxidation. A high chromium content lowers the grindability, while raising the hardening temperature of the material, which may lead to deformation of heat-treated parts.

Columbium (Cb). Columbium is similar in its effect to titanium, preventing the harmful carbide precipitation which causes an intergranular corrosion.

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Lead (Pb). Lead improves machinability, being added to the alloy in quantities of 0.15 to 0.35 percent. It must be finely dispersed within the material.

Molybdenum (Mo). This element aids the penetration of hardness while increasing the toughness of the steel. It ranges usually from 0.1 to 0.4 percent. In small amounts, molybdenum aids the toughness and deep-hardening properties of the material. In higher concentrations, such as those used for high-speed steels, it replaces tungsten in some cases. Molybdenum will protect the material from effects of creep and improve its hot hardness.

Nickel (Ni). Nickel is found in the steel in quantities of 1 to 4 percent, although alloy steels containing up to 35 percent of Ni may be found, with steels called "super alloys " such as Monel at 67 percent of Ni, Inconel at 77 percent, and Hastelloy D at 85 percent. Nickel increases the toughness and strength of the material, plus wear, and impact resistance at low temperatures.

Tellurium (Te). Used in the amount of approximately 0.05 percent, tellurium improves machinability.

Titanium (Ti). With similar range of influence to columbium, titanium provides the steel material with resistance to the harmful effects of carbon precipitation. When added to low-carbon steels, titanium makes them more suitable for porcelain enameling.

Tungsten (W). This element is often used in large quantities of 17 to 20 percent, usually in combination with chromium and other alloying elements. It is the basic ingredient of high-speed steels, which permits them to retain their hardness even at high temperatures on account of tungsten's good hot-hardness qualities. Tungsten is irreplaceable where a high-heat environment is encountered or where considerable wear resistance is required. In lesser percentages, tungsten is used to produce a fine, dense grain of the material.

Vanadium (V). When added to steel, most often in quantities of 0.15 to 0.20 percent, vanadium retards grain growth and refines the carbide structure, which results in improved forgeability. Vanadium also enhances the material's shock resistance and improves its hardness and resistance to wear and abrasion. Too much vanadium lowers the grindability of the material.

14-2 MECHANICAL PROPERTIES OF METAL MATERIALS

Mechanical properties influence the behavior of materials and subsequently the behavior of products which they may form already during the manufacturing process and later in service as well. Various mechanical properties should be combined to suit the appropriate application, as some properties may be harmful where others are beneficial, and vice versa.

Mechanical properties may be roughly listed as shown in Table 14-1.

14-2-1 Strength of Materials

The tensile strength of the material is a ratio of the force P to the original cross-section area A, against which the force is applied, or

$$S_s = \frac{P}{A} \tag{14-1}$$

The same formula may be used when assessing the real, or true, stress. In such a case, the area of cross section will be that obtained after the cessation of the applied force.

Strength of the material may be described as the amount of force needed to produce its failure. The ability of the material not to become a victim to plastic deformation is expressed

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TABLE 14-1 Mechanical Properties of Materials

Property	Symbol	Description	Units of measure: English	Units of measure: SI
Stress	S	Force/unit area	lb/in.^{2}	MPa
Strain	e	Deformation, $\Delta L/L$		
Modulus, elasticity	E	Stress/elastic strain	lb/in.^{2}	MPa
Modulus, shear	G	Unit stress/unit strain	lb/in.^{2}	MPa
Strength, yield	S_y	Resistance to initial plastic deformation	lb/in.^{2}	MPa
Strength, tensile	S_T	Maximum strength	lb/in.^{2}	MPa
Strength, ultimate	S_u	See Strength, tensile	lb/in.^{2}	MPa
Ductility		Plastic strain at failure		
Elongation		$(L_1 - L_0)/L_0$	%	%
Reduction of area		$(A_0 - A_1)/A_0$	%	%
Toughness		Energy for failure by fracture	ft-lb	joules
Hardness		Resistance to indentation	Per method used	

by the amount of its *yield strength* S_y. It is the ratio of the force within the yield strength range and the cross-sectional area of the test piece. Sometimes a *yield point* is given instead, especially where the material hardness is low.

14-2-2 Hardness of Materials

Hardness of materials may be tested by several methods, all of them assessing resistance to penetration of the surface. Naturally, hardness and strength are therefore quite similar. Some most often used methods of measurement follow, while a comparison of hardness scales is offered in Tables 14-2 and 14-3.

The *Rockwell hardness test (HR)* is performed by assessing the depth of penetration of a steel ball or a diamond spheroconical penetrating tool into the material's surface. The hardness evaluation is proportional to the depth of the indentation produced, with higher numbers assigned to harder materials.

There are several Rockwell hardness scales, with their fields of application reserved for certain areas. The most common scales and their descriptions are shown in Table 14-4.

The *Brinell hardness test* (*HB*) for assessing the hardness of metallic materials is performed by applying a certain specific load on a steel ball of predetermined diameter, forcing it into a tested material. The diameter of resulting indentation is measured and the appropriate Brinell hardness number is calculated with the aid of a formula

$$HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \tag{14-2}$$

where P = load applied, kg
D = diameter of ball, mm
d = diameter of impression, mm

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TABLE 14-2 Comparison of Hardness Scales for Hardened Steel

				Rockwell						
Rockwell scale C	Brinell *HB*	Vickers *HV*	Shore scleroscope	Scale A	Scale D	15-N	30-N	45-N	Scale G	Knoop *HK*
20	230	236	34	60.5	40.0	69.5	41.5	19.5	81.0	251
21	235	241	35	61.0	41.0	70.0	42.5	20.5	82.5	256
22	240	246	35	61.5	41.5	70.5	43.0	22.0	83.5	261
23	245	251	36	62.0	42.5	71.0	44.0	23.0	84.5	266
24	250	257	37	62.5	43.0	71.5	45.0	24.0	86.0	272
25	255	264	38	63.0	44.0	72.0	46.0	25.5	87.0	278
26	260	271	38	63.5	44.5	72.5	47.0	26.5	88.0	284
27	265	278	40	64.0	45.5	73.5	47.5	28.0	89.0	290
28	270	285	41	64.5	46.0	74.0	48.5	29.0	90.0	297
29	276	293	41	65.0	47.0	74.5	49.5	30.0	91.0	304
30	283	301	42	65.5	47.5	75.0	50.5	31.5	92.0	311
31	290	309	43	66.0	48.5	75.5	51.5	32.5		318
32	297	317	44	66.5	49.0	76.0	52.0	33.5		326
33	305	325	46	67.0	50.0	76.5	53.0	35.0		334
34	313	334	47	67.5	50.5	77.0	54.0	36.0		342
35	322	343	48	68.0	51.5	78.0	55.0	37.0		351
36	332	353	49	68.5	52.5	78.5	56.0	38.5		360
37	342	363	50	69.0	53.0	79.0	56.5	39.5		370
38	352	373	51	69.5	54.0	79.5	57.5	41.0		380
39	362	383	52	70.0	54.5	80.0	58.5	42.0		391
40	372	393	54	70.5	55.5	80.5	59.5	43.0		402
41	382	403	55	71.0	56.0	81.0	60.5	44.5		414
42	393	413	56	71.5	57.0	81.5	61.5	45.5		426
43	404	424	57	72.0	57.5	82.0	62.0	46.5		438
44	415	435	58	72.5	58.5	82.5	63.0	48.0		452
45	426	446	60	73.0	59.0	83.0	64.0	49.0		466
46	437	458	62	73.5	60.0	83.5	65.0	50.0		480
47	448	471	63	74.0	60.5	84.0	66.0	51.5		495
48	460	485	64	74.5	61.5	84.5	66.5	52.5		510
49	472	498	66	75.5	62.0	85.0	67.5	54.0		526
50	484	513	67	76.0	63.0	85.5	68.5	55.0		542
51	496	528	68	76.5	64.0	86.0	69.5	56.0		558
52	509	545	69	77.0	64.5	86.5	70.5	57.5		576
53	522	562	71	77.5	65.5	87.0	71.0	58.8		594
54	534	580	72	78.0	66.0	87.5	72.0	59.5		612
55	547	598	74	78.5	67.0	88.0	73.0	61.0		630
56	560	617	75	79.0	67.5	88.5	74.0	62.0		650
57	573	636	76	79.5	68.5	89.0	75.0	63.0		670
58	587	655	78	80.0	69.0	89.3	75.5	64.0		690
59	600	675	80	80.5	70.0	89.5	76.5	65.5		710
60	614	695	81	81.0	71.0	90.0	77.5	66.5		732
61		716	83	81.5	71.5	90.5	78.5	67.5		754
62		739	85	82.5	72.5	91.0	79.0	69.0		776
63		763	87	83.0	73.0	91.5	80.0	70.0		799
64		789	88	83.5	74.0	91.8	81.0	71.0		822
65		820	91	84.0	74.5	92.0	82.0	72.0		846
66		854	92	84.5	75.5	92.5	83.0	73.0		870
67		894	95	85.0	76.0	93.0	83.5	74.5		895
68		942	97	85.5	77.0	93.2	84.5	75.5		920
69		1004		86.0	78.0	93.5	85.0	76.5		946
70		1076		86.5	78.5	94.0	86.0	77.5		972

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TABLE 14-3 Comparison of Hardness Scales for Nonhardened Steel, Iron, and Nonferrous Metals

Rockwell				Rockwell							
Scale B	Scale F	Brinell *HB*	Vickers *HV*	Scale G	15-T	30-T	45-T	Scale E	Scale K	Scale A	Knoop *HK*
0	57.0	53				15.0		57.0	21.0		67
1	57.5				61.0	16.0		57.5	22.0		
2	58.0	54			61.5	16.5		58.0	23.0		68
3	59.0					17.0		58.5	23.5		
4	59.5				62.0	18.0		59.0	24.5		
5	60.0	55			62.5	18.5		60.0	25.5		69
6	60.5					19.5		60.5	26.0		
7	61.0	56			63.0	20.0		61.0	27.0		
8	61.5				63.5	20.5		61.5	28.0		71
9	62.0					21.5		62.0	29.0		
10	63.0	57			64.0	22.0		62.5	29.5		
11	63.5					23.0		63.5	30.5		73
12	64.0				64.5	23.5		64.0	31.5		
13	64.5	58			65.0	24.0		64.5	32.0		
14	65.0					25.0		65.0	33.0		
15	65.5	59			65.5	25.5		65.5	34.0	20.0	76
16	66.0				66.0	26.0		66.5	35.0	20.5	
17	66.5	60				27.0		67.0	35.5	21.0	
18	67.0				66.5	27.5		67.5	36.5		
19	68.0	61			67.0	28.5		68.0	37.5	21.5	79
20	68.5					29.0		68.5	38.0	22.0	
21	69.0	62			67.5	29.5		69.5	39.0	22.5	
22	69.5					30.5		70.0	40.0	23.0	
23	70.0	63			68.0	31.0		70.5	41.0	23.5	82
24	70.5				68.5	32.0		71.0	41.5	24.0	
25	71.0	64				32.5		72.0	42.5		

26	72.0	65			69.0	33.0		72.5	43.5	24.5	
27	72.5				69.5	34.0		73.0	44.5	25.0	85
28	73.0	66				34.5		73.5	45.0	25.5	
29	73.5				70.0	35.5	1.0	74.0	46.0	26.0	
30	74.0	67			70.5	36.0	2.0	75.0	47.0	26.5	
31	74.5	68				36.5	3.0	75.5	48.0	27.0	88
32	75.0				71.0	37.5	4.0	76.0	48.5	27.5	89
33	75.5	69				38.0	5.0	76.5	49.5		90
34	76.5	70			71.5	38.5	6.0	77.0	50.5	28.0	91
35	77.0	71			72.0	39.5	7.0	78.0	51.5	28.5	92
36	77.5					40.0	8.0	78.5	52.0	29.0	93
37	78.0	72			72.5	40.5	9.0	79.0	53.0	29.5	94
38	78.5	73			73.0	41.5	10.0	79.5	54.0	30.0	95
39	79.0	74				42.0	11.0	80.0	54.5	30.5	96
40	79.5				73.5	43.0	12.5	81.0	55.5		97
41	80.5	75			74.0	43.5	13.5	81.5	56.5	31.0	98
42	81.0	76				44.0	14.5	82.0	57.5	31.5	99
43	81.5	77			74.5	45.0	15.5	82.5	58.0	32.0	100
44	82.0	78			75.0	45.5	16.5	83.5	59.0	32.5	101
45	82.5	79				46.0	17.5	84.0	60.0	33.0	102
46	83.0				75.5	47.0	18.5	84.5	61.0	33.5	103
47	84.0	80			76.0	47.5	19.5	85.0	61.5	34.0	104
48	84.5	81				48.5	20.5	85.5	62.5	34.5	105
49	85.0	82			76.5	49.0	22.0	86.5	63.5		106
50	85.5	83		2.5	77.0	49.5	23.0	87.0	64.5	35.0	107
51	86.0	84		4.0		50.5	24.0	87.5	65.0	35.5	108
52	86.5	85		5.5	77.5	51.0	25.0	88.0	66.0	36.0	109
53	87.0	86		7.0	78.0	51.5	26.0	89.0	67.0	36.5	110
54	87.5	87		8.5		52.5	27.0	89.5	68.0	37.0	111
55	88.0	89	100	10.0	78.5	53.0	28.0	90.0	68.5	37.5	112
56	89.0	90	101	11.5	79.0	54.0	29.0	90.5	69.5		114
57	89.5	91	103	13.0		54.5	30.0	91.0	70.5	38.0	115

(*Continued*)

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TABLE 14-3 Comparison of Hardness Scales for Nonhardened Steel, Iron, and Nonferrous Metals (*Continued*)

Rockwell				Rockwell							
Scale B	Scale F	Brinell *HB*	Vickers *HV*	Scale G	15-T	30-T	45-T	Scale E	Scale K	Scale A	Knoop *HK*
58	90.0	92	104	14.5	79.5	55.0	31.0	92.0	71.0	38.5	117
59	90.5	94	106	16.0	80.0	56.0	32.0	92.5	72.0	39.0	118
60	91.0	95	107	17.5		56.5	33.5	93.0	73.0	39.5	120
61	91.5	96	108	19.0	80.5	57.0	34.5	93.5	74.0	40.0	122
62	92.0	98	110	20.5		58.0	35.5	94.5	74.5	40.5	124
63	93.0	99	112	22.0	81.0	58.5	36.5	95.0	75.5	41.0	125
64	93.5	101	114	23.5	81.5	59.5	37.5	95.5	76.5	41.5	127
65	94.0	102	116	25.0		60.0	38.5	96.0	77.5		129
66	94.5	104	117	26.5	82.0	60.5	39.5	97.0	78.0	42.0	131
67	95.0	106	119	28.0	82.5	61.5	40.5	97.5	79.0	42.5	133
68	95.5	107	121	29.5		62.0	41.5	98.0	80.0	43.0	135
69	96.0	109	123	31.0	83.0	62.5	42.5	99.0	81.0	43.5	137
70	97.0	110	125	32.5	83.5	63.5	43.5	99.5	81.5	44.0	139
71	97.5	112	127	34.5		64.0	44.5	100.0	82.5	44.5	141
72	98.0	114	130	36.0	84.0	65.0	45.5		83.5	45.0	143
73	98.5	116	132	37.5	84.5	65.5	46.5		84.5	45.5	145
74	99.0	118	135	39.0		66.0	47.5		85.0	46.0	147
75	99.5	120	137	41.0	85.0	67.0	48.5		86.0	46.5	150
76		122	139	42.5		67.5	49.0		87.0	47.0	152
77		124	141	44.0	85.5	68.0	50.0		88.0	48.0	155
78		126	144	46.0	86.0	69.0	51.0		88.5	48.5	158
79		128	147	47.5		69.5	52.0		89.5	49.0	161
80		130	150	49.0	86.5	70.0	53.0		90.5	49.5	164
81		133	153	51.0	87.0	71.0	54.0		91.0	50.0	167
82		135	156	52.5		71.5	55.0		92.0	50.5	170
83		137	159	54.0	87.5	72.0	56.0		93.0	51.0	173

84	140	162	56.0	88.0	73.0	57.0	94.0	52.0	176
85	142	165	57.5		73.5	58.0	94.5	52.5	180
86	145	169	59.0	88.5	74.0	58.5	95.5	53.0	184
87	148	172	61.0	89.0	74.5	59.5	96.5	53.5	188
88	151	176	62.5		75.0	60.5	97.0	54.0	192
89	154	180	64.0	89.5	75.5	61.5	98.0	55.0	196
90	157	185	66.0	90.0	76.0	62.5	98.5	55.5	201
91	160	190	67.5		77.0	63.5	99.5	56.0	206
92	163	195	69.0	90.5	77.5	64.5	100.0	56.5	211
93	167	200	71.0	91.0	78.0	65.5		57.0	216
94	171	205	72.5		78.5	66.0		57.5	221
95	175	210	74.0	91.5	79.0	67.0		58.0	226
96	179	216	76.0		80.0	68.0		59.0	231
97	184	222	77.5	92.0	80.5	69.0		59.5	236
98	189	228	79.0		81.0	70.0		60.0	241
99	195	234	81.0	92.5	81.5	71.0		61.0	246
100	201	240	82.5	93.0	82.0	72.0		61.5	251

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TABLE 14-4 Rockwell Hardness Scales

Scale	Tester	Force, kg	Usage
A	Diamond point	60	For extremely hard materials
B	ϕ0.062-in ball	100	Medium-hard materials, such as annealed low-carbon and medium-carbon steels
C	Diamond point	150	Continuation of B scale
D	Diamond point	100	Same as C-scale testing with a lighter testing load
E	ϕ0.125-in ball	100	For very soft materials
F	ϕ0.062-in ball	60	Continuation of E scale
G	ϕ0.062-in ball	48	Testing of metals harder than those using B scale
H	ϕ0.125-in ball	60	For softer materials
K	ϕ0.125-in ball	150	For softer materials

Vickers hardness testing (HV) is somewhat similar to the Brinell method. The penetrator is a square-based diamond pyramid, angled toward its point at 136°. The numerical value of the hardness is calculated from the ratio of the load to the area of the impression as

$$HV = \frac{2P\sin(\alpha/2)}{d^2} = \frac{1.8544P}{d^2} \tag{14-3}$$

where P = load applied, kg
d = diagonal measurement of indentation, mm
α = face angle of pyramid, 136°

The *Knoop hardness test* is used for evaluation of extremely thin materials, plated surfaces, very brittle or very hard surfaces, or where the load must be kept below 3.6 kg. The hardness number is obtained by dividing the applied load by the area of indentation. The penetrator in this case is a special rhombic-based pyramid indenter, made of industrial diamond, with one of the angles between the intersections of its four-faceted shape ground to an angle of 172.5° while the other angle is 130°. The calculation of the hardness value is

$$H_K = \frac{P}{0.07028d^2} \tag{14-4}$$

where P = load applied, kg
d = length of a long diagonal distance (mm)
0.07028 = constant, corresponding to the standard angles of the pyramidal shape

Shore's scleroscope testing evaluates hardness in terms of elasticity. A diamond-pointed tester is dropped from a predetermined height onto the tested material. On falling upon its surface, the tester rebounds, the height of its rebound indicating the hardness of the material. With harder materials, this distance is greater; with softer materials it is shorter. Shore's hardness is often used to specify the toughness of rubber or urethane.

14-2-3 Toughness of Materials

The degree of toughness actually assesses the amount of energy required to produce a breakage within the material. This is not the same property as the material's strength, which shows its reaction to the stresses, producing a deformation within its structure.

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MATERIALS AND SURFACE FINISH

Toughness is composed of two components: an elastic component (strength) and a plastic component (ductility). The elastic portion of toughness increases in congruence with the increasing hardness, while at the same instant the plastic component decreases.

The toughness of a material is given in terms of energy needed to break a sample piece. This energy is specified in foot-pounds or joules and is measured by using the Izod (or Charpy) testing arrangement, where a test specimen is broken by an impact of a swinging pendulum. Also tensile testing and torsion testing has been used in assessment of material toughness.

14-2-4 Deformation and Ductility

Deformation of the material occurs where the stress (force) is applied to its mass, coercing its shape to follow the direction of its application. There are two types of deformation: elastic and plastic. In *elastic deformation,* the material is altered within its elastic limits, which means that on release of force it returns to its original size and shape.

Plastic deformation occurs where deviation in shape due to the application of force exceeds the material's elastic limit, in which case the deformation is permanent, and on release of the force the material will not return to its original form and shape. Examples of plastic deformation are bending, forming, and drawing operations. Examples of elastic deformation can be found in spring materials.

The initial strain of the material is proportional to the stress applied against it. The modulus of elasticity, or Young's modulus E, depicts the stress and strain relationship as

$$E = \frac{S}{e} \quad \text{lb/in.}^2 \text{ or MPa} \tag{14-5}$$

where S = stress
e = strain

A major characteristic of the material, influencing its behavior under the application of stress (force), is its ductility. *Ductility* may be expressed as the percentage of elongation, in which case it depends on the result of the relationship

$$\frac{L_1 - L_0}{L_0} = \frac{\Delta L}{L_0} \tag{14-6}$$

where L_0 = original length of part
L_1 = final length of part

Ductility assessed through this method is based on the amount of elongation of the sample specimen. Since the greater amount of plastic deformation occurs in the necked area of the tested piece, the percentage of elongation must be specified as dependent on the length of the gauge (see Fig. 14-3).

Ductility may also be evaluated on the grounds of the reduction in area at the point of fracture as

$$\frac{A_0 - A_1}{A_0} = \frac{\Delta A}{A_0} \tag{14-7}$$

High ductility means the neck of the fracture will be quite small in cross section before it breaks off.

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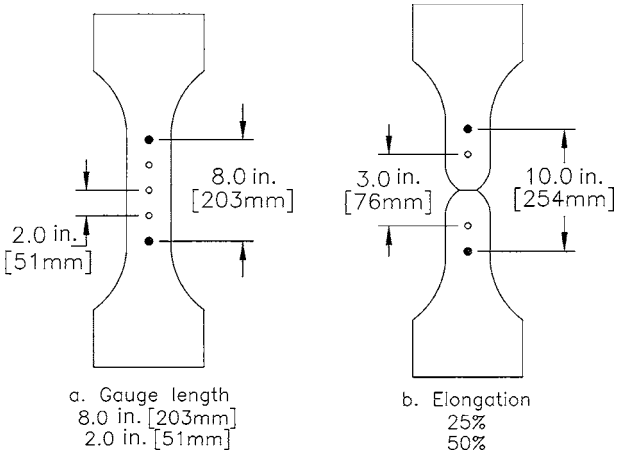

FIGURE 14-3 Tensile strength testing.

Deformation tendency of a steel may be caused by a combination of its properties, as brought together by different manufacturing methods. For example, a previously cold-worked steel material will display a marked tendency to distortion after machining. It should never be finished to size without first being stress-relieved. The heat-treatment process may produce additional dimensional changes within such material, or a deviation from straight, round, and the like. Therefore, only after stress relieving should such parts be finished and their critical dimensions tightened. Areas that are most susceptible to distortions are those where the greatest amount of machining was performed and subsequently where the greatest amount of stress was produced.

Even a previously cold-rolled material, when cold-worked afterward, will experience changes within its structure, affecting it into its very core. The amount of additional cold working may not be extensive; a 5 percent reduction due to rolling is enough to bring about considerable changes.

For one thing, the cold working produces an increase in the material's hardness, or so-called strain hardening. With approximately 15 percent reduction in thickness, the effect of hardening on the layers of material closest to the surface is guaranteed. However, with a reduction in size amounting to up to 25 percent, the whole thickness of the stock will be hardened, or strain-hardened.

Hot-rolled steels are not excessively influenced by the cold work instituted afterward. Even though such treatment increases their hardness, the amounts are small in comparison with cold-rolled stock. Where in hot-rolled steel the surface hardness may be increased some 30 percent, the same amount of cold work will produce roughly a 60 percent increase of hardness in cold-rolled material.

14-2-5 Thermal Properties

Where the temperature is used to measure the amount of thermal activity, heat content depicts the amount of thermal energy.

Heat capacity is the change in heat content of the test specimen, given in either °F or °C or other units. The *specific heat* is the ratio of the heat capacity of that particular material to the heat capacity of water.

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Thermal conductivity k is a measure of heat transfer, utilized with the aid of a particular material. The amount of thermal conductivity is a constant, relating the heat flux Q to the thermal gradient $\Delta T/\Delta x$ or

$$Q = k\frac{\Delta T}{\Delta x} = k\frac{T_1 - T_0}{x_1 - x_0} \tag{14-8}$$

where T = temperature value
x = thickness of material

The value of the thermal conductivity Q can be expressed as the ratio of energy to area A by time t, or

$$Q = \frac{\text{energy}}{At}$$

Thermal expansion measures the expansion in length of a heated specimen. The increase in length ΔL is considered proportional to the change in temperature ΔT, or

$$\frac{\Delta L}{L} = \alpha_L \Delta T \tag{14-9}$$

where α_L = coefficient of linear expansion

Where assessing the volumnar expansion, the coefficient α_υ depicts the volumnar change $\Delta V/V$. $\alpha_\upsilon = 3\alpha_L$, and the formula becomes

$$\alpha_\upsilon \Delta T = 3(\alpha_L)\Delta T = \frac{\Delta V}{V} \tag{14-10}$$

14-2-6 Electrical Properties

Metals, like semiconductors, conduct an electrical charge when positioned within an electrical field. The conductivity depends on the charge carried, on the mobility of the carrier, and on the number of carriers. The conductivity is the opposite, or the reciprocal of the resistivity ρ. It can be expressed as

$$\sigma = 1/\rho = nq\mu \tag{14-11}$$

where σ = conductivity
ρ = resistivity
n = number of carriers
μ = carriers' mobility
q = charge

Resistivity is considered to be an electrical property of material. In parts of uniform geometry, resistivity may be converted to the material's resistance R, as

$$R = \frac{\rho L}{A} \tag{14-12}$$

where A = cross-sectional area
L = length of the piece

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14-2-7 Endurance and Fatigue

Fatigue will impair the performance of parts or assemblies over a period of time and after going through a certain number of work cycles. The effects of fatigue may be seen on a round metal bar, with both ends subjected to loading of the same type as that of a beam. A compressive force is acting against its upper surface, creating a tension within the bottom layers. Such an arrangement, if allowed to rotate, will definitely produce a dimensional alteration of the specimen. After the completion of a few hundred thousand cycles, even a test piece made of good grade steel may begin to show a fatigue-dependent distortion, such as the one in Fig. 14-4.

For comparison, a similar specimen exposed to a loading of approximately 60,000 lb/in.^{2} broke apart under the effect of fatigue on completion of 100,000 revolutions.

The endurance limit is greater where the specimen's surface is polished. Subsequently, corrosion lowers this limit, as well as any sharp corners, notches, and similar sharp indentations of the part's surface. Even the width of a groove on a shaft has a definite effect on the endurance limit of such a part. If such a shaft has an endurance limit of 35,000 lb/in.^{2}, a circular notch may lower this value to some 85 percent, which is 30,000 lb/in.^{2}.

A comparison of the performance of notched parts is offered here, as based on the actual testing, where a specimen of 1-in-diameter heat-treated steel bar was subjected to a surface alteration by notching and rotated in the testing machine described earlier. The endurance limit of the material was 75,000 lb/in.^{2}. A nice, rounded fillet, as shown in Fig. 14-5*a*, made the part sustain 80,000 revolutions before it broke apart. A bit sharper fillet, shown in Fig. 14-5*b*, produced 75,000 revolutions. A sharp, square groove (Fig. 14-5*c*) lasted 20,000 revolutions. A very sharp V notch (Fig. 14-5*d*) broke the test piece after 14,000 revolutions.

From the above, the influence of the sharpness of grooving on the life expectancy of the part is more than obvious.

Another detrimental effect on the part's endurance limit may be attributed to the decarburization process applied to it. Where an annealed steel has a strength of approximately 60,000 lb/in.^{2}, its high-strength counterpart boasts 200,000 lb/in.^{2}, with a fatigue strength of some 110,000 lb/in.^{2}. However, if a part made of such high-strength material is decarburized, its endurance limit drops to 60,000 lb/in.^{2}. There is no size change, no length alteration, no difference in appearance. Only the endurance limit drops to a meager 60,000 lb/in.^{2}, which is equivalent to the strength of an annealed steel.

Where a grooved shaft was subjected to decarburization, it broke off within the area of the groove. Leaf springs and valve springs are greatly affected by decarburization, which usually results in their failure later in service.

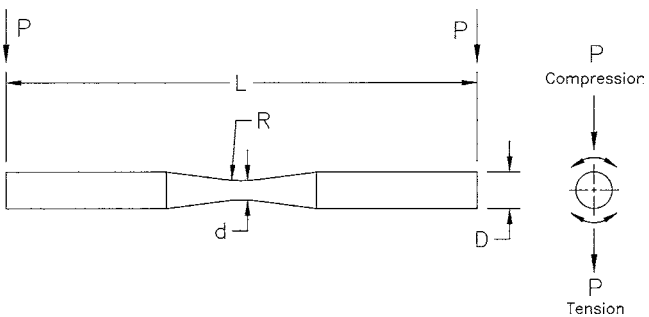

FIGURE 14-4 Endurance limit testing.

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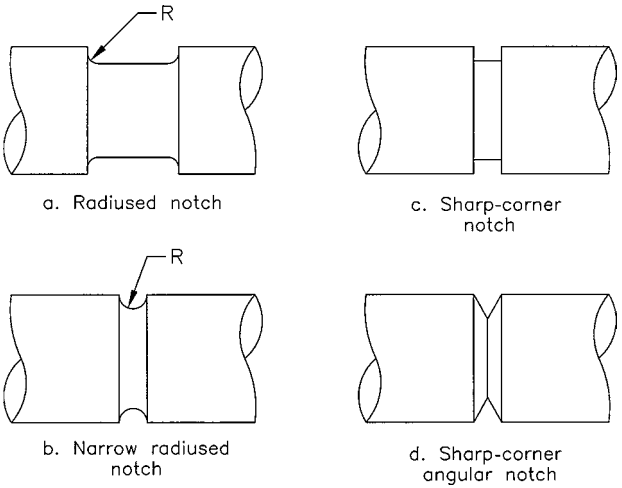

FIGURE 14-5 Notching and its influence on the part.

In Fig. 14-6, depicting the drop in the endurance limit for various materials, the lines shown are for the specific material's surface conditions: (*a*) polished, (*b*) ground, (*c*) roughed, (*d*) with a sharp circumferential indentation, or grooved, (*e*) with hardened skin after cold rolling, (*f*) surface corroded by water, (*g*) surface corroded by salt water.

Notching is not the only means of producing fatigue and lowering the endurance limit of parts. The same may be achieved with any sharp edge, any thickness inequality, and many other deviations from a sound design. Finite-element analysis reveals clearly and in colors, the accumulation of stresses within a body of a part. The most crowded areas are exactly those mentioned earlier.

A screw, shown in Fig. 14-7, will gain in strength if a hole is drilled through its center. Naturally, it must not be in any way located near the roots of threads. A small opening proportionally equal to the one shown will relieve some inner stresses imposed on the screw by the process of tightening it, which actually is a process of applying pressure toward some portions of its thread. With such an empty space to accommodate for any irregularities due to the loading, the thread grows stronger and the functionability of the screw is enhanced.

Another contributing factor is a shape of the central opening, which is that of a continuous supporting arch, not unlike those used in medieval times for support of heavy stone structures. The support of such a continuous arch is flexible enough, yet firm and unyielding.

14-2-8 Wear

Wear may be classified as removal of surficial layers of material, caused by the part's performance in the work process. Most wear is attributable to adhesion and diffusion of material, chipped off the tooling or workpiece, but additional causes of wear mechanisms are given in the following list:

- **Abrasion wear** is usually caused by impurities such as dirt, fragments of metal, and similar objects within the working areas of parts. By passing over the tool surface, they may mechanically attack it by scratching its outer layer.

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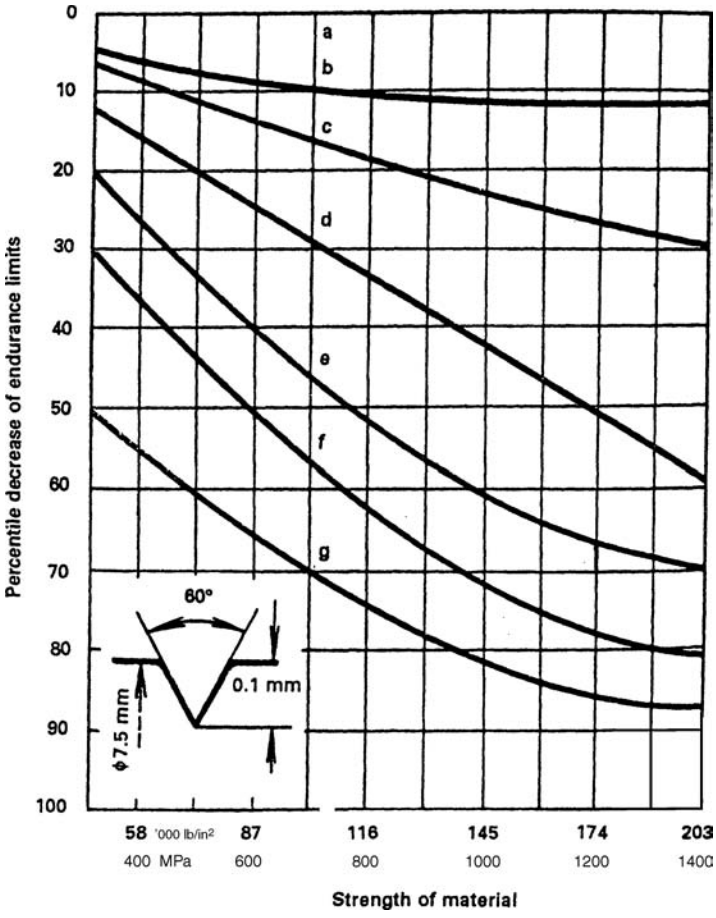

FIGURE 14-6 Lowered endurance limit due to variation of the surface finish. (*From Svatopluk Černoch,* "Strojně technická příručka," 1977. *Reprinted with permission from SNTL Publishers, Prague, CZ.*)

- **Adhesion wear** is caused by the friction between the tooling and the workpiece. The heat of friction tears off small pieces of the tool material, depositing it either with chips or with the workpiece.
- **Diffusion wear** occurs where a localized high heat, produced by the manufacturing process, forces the atoms within the material's metallic crystal lattice to move from one point to another. Such a movement creates a shift within the material, during which the elements transfer in the direction of a different rate of their concentration. The surface of the part becomes depleted and may disintegrate and dust away or be removed otherwise.
- **Electrochemical wear** is found where an interaction between the material of tooling and that of the part is achieved in an environment created by a cutting fluid. Such a wear mechanism forces the ions to pass freely between the tool and the workpiece, resulting in oxidation of the tool surface.

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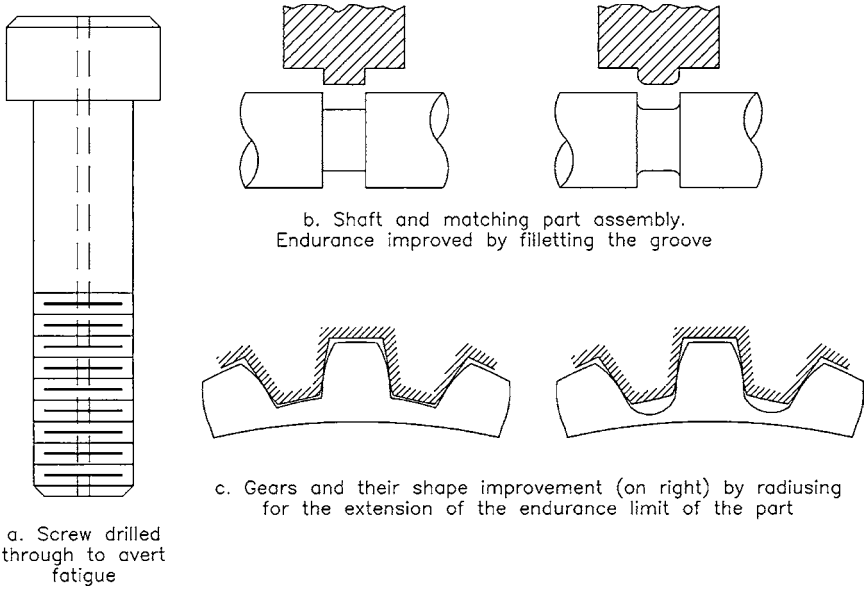
a. Screw drilled through to avert fatigue
b. Shaft and matching part assembly. Endurance improved by filletting the groove
c. Gears and their shape improvement (on right) by radiusing for the extension of the endurance limit of the part

FIGURE 14-7 Alterations to improve the endurance limit of parts.

- **Pitting** may be classified as a result of compression-related surface failure. It is caused by a repeated action against the material surface, during which stresses are applied against the material outer layers. Pitting is frequently found to be a common defect in gear teeth.
- **Galling** is a metal-to-metal contact during the movement of tooling in the operation. It is described in Sec. 9-11-5, "Galling."
- **Creep** occurs in a stressed metal material, with neither the stress force nor the temperature being too high. The material, exposed to regular stresses of the work cycle, responds to their application by deforming elastically, which produces slight plastic changes along the grain boundaries or at possible internal flaws. With the continuation of stress application, the material begins to very slowly flow under its force, until finally, when a sufficient strain is created, it extends in shape, with subsequent reduction of the area closest to the stress application. If such a process continues, it will lead to total fracture of that material.

14-2-9 Corrosion

The most frequent corrosion is caused by oxidation of metals and alloys, in which case the reaction itself produces a deposition within the area of affliction. The speed and the spread of corrosion depend on the characteristics of this growth and on the possibility of its penetration enhanced by additional influences. Corrosion is often connected with the transfer of electrical particles on the atomic level, and for that reason the electrical properties of the corrosive growth are pertinent.

Once a deposit produced by the corrosive action is formed, its kinetics is given by the character of its particles. The main influence is the diffusion of oxygen ions and ions of metal through its barrier.

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However, not all materials form layers of residue of their corrosive action. Some materials, such as potassium, lithium, barium, and strontium, actually don't. Also the reaction of chloride with iron at high temperatures does not produce the corrosive residue. A list of selected corrosively-reacting materials is shown in Table 14-5.

With electrochemical corrosion, the mechanism is the same as that of galvanic cell: With greater difference between the potentials of two metals, the initial corrosive reaction is more pronounced. For example, zinc and aluminum, when immersed in a solution of sodium chloride, have a difference of potential of 300 mV, whereas zinc with copper has a 700 mV difference. This means that when paired with copper, zinc will corrode faster.

Every corrosion contains two opposite sides of its reaction: anodic and cathodic. Cathodic reaction, being depolarizating in its origin, reduces the amount of anodic influence, while anodic reaction, which is oxidation, promotes corrosion. The two combined interactions are generally summed under the title of corrosion, which is an oxidating and reductive process.

Where a protective coating is created within the metal material surface, it is called a passive coating. Passivity may be defined as a state in which metals or alloys are found to be resistant to corrosion, even though being exposed to a corrosion-inducing environment. Some consider passivity to be due to a retardation of either the anodic or the cathodic reaction. Others promote the *adsorption theory,* which claims the passivity to be a phenomenon depending on the adsorption of some elements, mainly oxygen, from the solution off the metal's surface. Still another theory considers passivity as attributable to a thin film of a compound, such as a third phase on the metal surface.

Metals that can be passivated are aluminum, chromium, manganese, titanium, vanadium, iron, nickel, cobalt, molybdenum, niobium, tungsten, and others. For industrial purposes several of their alloys are important, such as carbon and low-carbon steel, stainless steel, with alloying elements such as chromium, titanium, and nickel. The composition of the metal is the main factor constituting its suitability for passivation.

14-3 TESTING OF MECHANICAL PROPERTIES

Mechanical properties of materials are assessed through actual testing, with results of these tests recorded for future reference. The most common test is the hardness test, which is performed using several testing methods. The process is described in Sec. 14-2-2, "Hardness of Materials." Additional testing of mechanical properties is as follows.

14-3-1 Static Tensile Testing

Static tensile testing is performed by applying a static load to the tested material. The testing process is free from sudden impacts, load cycling, or abrupt changes. The amount of force, if increased, is regulated slowly and gradually.

Static load testing is performed mainly to assess the elongation of the material, and the testing records should include the amount of elongation with reference to the applied force. Marginally, torsion testing and compression testing is performed similarly.

14-3-2 Izod Impact Testing

Izod impact testing (or Charpy) is used to ascertain the toughness of a material. A notched bar of steel is attached into the vise and a pendulum type of hammer is allowed to drop onto the tested piece to break it (Fig. 14-8). A ductile material will need a greater amount of energy

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TABLE 14-5 Materials with Corrosive Influence

		Influence-exerting material										
No.	Material, basic	1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*
1.	Carbon and low-carbon steel	—	B	B	B	B	B	A	A	A	B	B
2.	Stainless steel	A	—	A	A	A	A	A	A	A	A	A–B
3.	Nickel and its alloys	A	A	—	A	B	A	A	A	A	A	A–B
4.	Chromium	A	A	A	—	A	A	A	A	A	A	A
5.	Copper and its alloys	A	B	B	B	—	A	A	A	A	A	B
6.	Aluminum and alloys	B	B	B	B	C	—	A	A	B	A	C
7.	Zinc and its alloys	C	C	B	B	C	B	—	B	B	B	C
8.	Cadmium	B	B	B	B	B	B	A	—	A	A	B
9.	Magnesium and alloys	C	C	C	C	C	B	B	B	—	C	C
10.	Lead, tin, and alloys	A	B	A	B	B	A	A	A	A	—	B
11.	Ag, Au, Pd, Pt, Ta, Ti, Zr	A	A	A	A	A	A	A	A	A	A	—

*Numbers with an asterisk correspond with numbers of particular materials in the far left column. The reaction between any two materials may be read by finding the intersection of their respective lines and rows.

The explanation of listed values is as follows:

A: Corrosion within atmospheric environment is not possible.

B: A mild corrosive reaction may be observed between the two materials.

C: Corrosive reaction will occur.

Note: Ag = silver; Au = gold; Pd = palladium; Pt = platinum; Ta = tantalum; Ti = titanium; Zr = zirconium.

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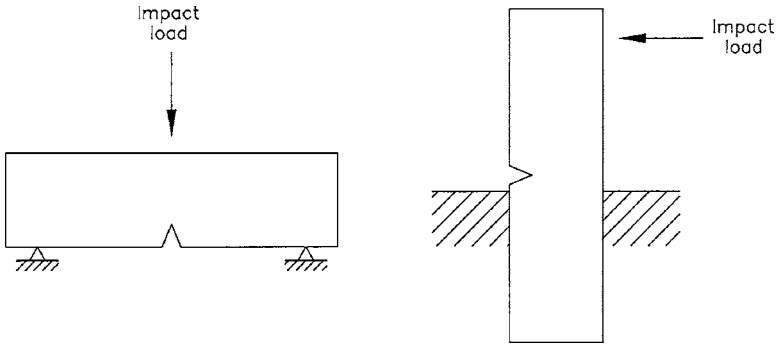

FIGURE 14-8 Impact load testing.

or more blows to be split than its nonconductive counterpart, even if they are both of the same strength. The ductile material is therefore tougher.

The orientation of applied force with reference to the material grain is important, as every material displays different results along its grain from those against it. Testing records must therefore include this information as well.

The impact testing method is very sensitive, assessing the properties of materials with regard to their manufacturing process and heat treatment. This type of testing is an irreplaceable method of evaluation of the quality of weldments. It is used for selection of proper materials for low-temperature applications, for testing of materials exposed to cyclic loading, and for evaluation of suitability of materials for steel constructions where the threat of fractures due to brittleness may be encountered.

The impact strength of a material is given in foot-pounds, indicating the amount of energy required for breaking the specimen in a single blow.

14-3-3 Fatigue Strength Testing

Testing of materials under cyclic loading is concerned with the fatigue testing of such materials. Fatigue-related failures are known for starting at much lower tensions than those of the material's tensile strength. However, some materials may sustain almost unlimited cyclic loading without succumbing to any changes. For that reason, cyclic loading, used in the fatigue assessment, is limited to a certain number of cycles. For steel, 10,000,000 cycles is often chosen, while for nonferrous materials up to 100,000,000 cycles may be performed.

Fatigue testing is often based on the evaluation of bending fatigue and is classified according to the direction of the load as

- Axial testing, or simple bending
- Bending during rotation
- Torsional testing

14-3-4 Testing of Breakability

Testing of a material's breakability is used for evaluation of its deformation properties in cold working and for assessment of its brittleness. This testing method is frequently used where a welded assembly's breakage is of concern or where a comparison of different welding methods is needed (Fig. 14-9).

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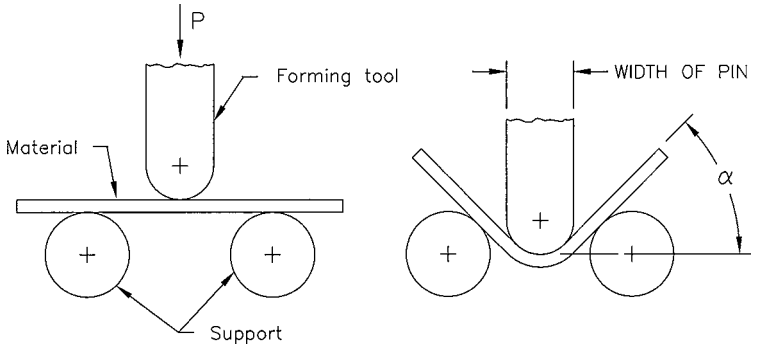

FIGURE 14-9 Test of breakability. (From *Svatopluk Černoch,* "Strojně technická příručka," *1977. Reprinted with permission from SNTL Publishers, Prague, CZ.*)

The amount of breakability is given by the size of angle α, while the width of the pin is specified in relation to the thickness of the tested material.

14-3-5 Testing of Drawability

Erichsen's test of drawability shown in Fig. 14-10 uses a ϕ20-mm drawing punch to press into a firmly retained sheet of metal until a breakage occurs. The result is given in the form of the height of a cup h, while a radial breakage spells the unsuitability of material for drawing. The condition of the drawn surface is observed; a rough surface coincides with a coarse grain.

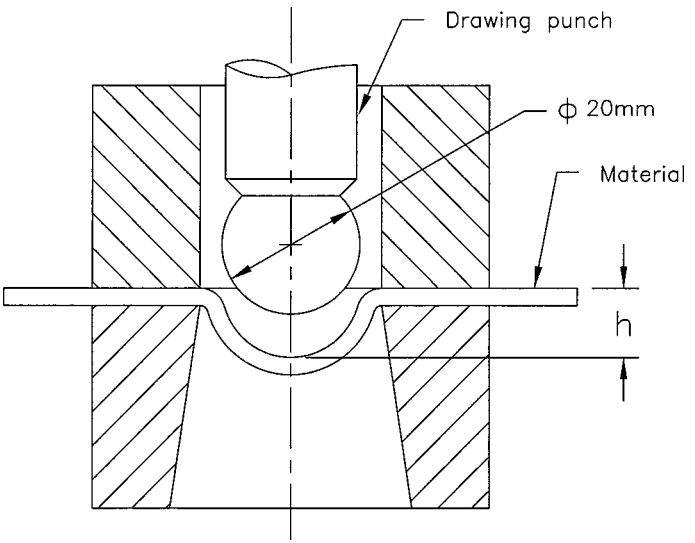

FIGURE 14-10 Drawability testing according to Erichsen. (*From Svatopluk Černoch,* "Strojně technická příručka," *1977. Reprinted with permission from SNTL Publishers, Prague, CZ.*)

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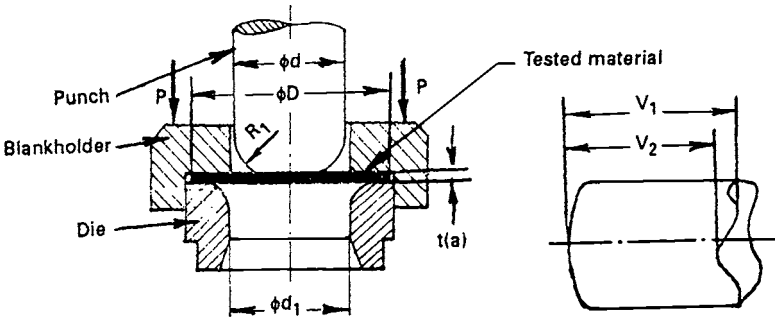

FIGURE 14-11 Cupping test for drawing purposes. Heights of cup sides (V_1, V_2), affected by anisotropy. (*From Svatopluk Černoch,* "Strojně technická příručka," *1977. Reprinted with permission from SNTL Publishers, Prague, CZ.*)

Evaluation of a material's anisotropy r is obtained through a cupping procedure, shown in Fig. 14-11.

The amount of aniostropy is given by the difference of measurements V_1 and V_2. Lately, the amount of normal anisotropy is often calculated from the results of regular tensile testing as in Eq. (14-13).

$$r = \frac{\log b_0/b}{\log a_0/a} \tag{14-13}$$

where b_0, a_0 = width or thickness, original
b, a = width or thickness after tensile testing

14-4 MATERIALS USED FOR TOOLING APPLICATIONS

The appropriate tool material must be carefully selected to be in accordance with requirements of the machining and fabricating process and the final product requirements. The most important points to consider are the necessary strength of the tooling and its toughness, hot hardness, thermal shock resistance, and chemical stability.

Since all tool steel materials are heat-treated for attainment of best properties, the behavior of steel material during the process of heat treatment is important. Any greater distortion produced by heat treatment should call for attention toward the selection of material, or part design, or manufacturing flawlessness, in this order. Some materials are more prone to distortion caused by heat treatment than others. Less stable steels need more conservative design methods in order to sustain the stress placed upon them by heat treatment. Long thin sections should be avoided or properly supported. Sharp corners, holes placed too close to the edges, or mixing of thin and thick sections should definitely be avoided. Some ideas are presented in Fig. 14-12.

The depth of surface hardening and the material's resistance to decarburization are important aspects of proper tool material selection. Naturally, the machinability of the material is of essence, as a tool made of material which is difficult to machine will cost much more to produce than its counterpart made of easily machinable material.

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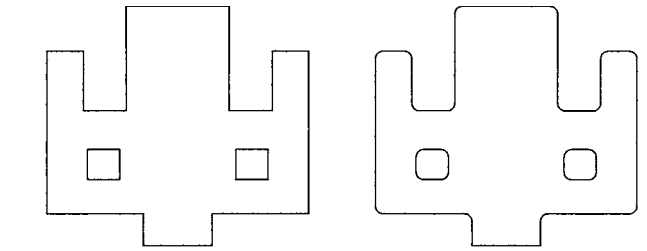
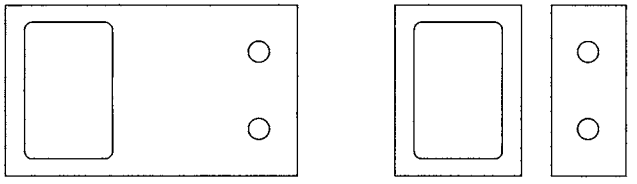
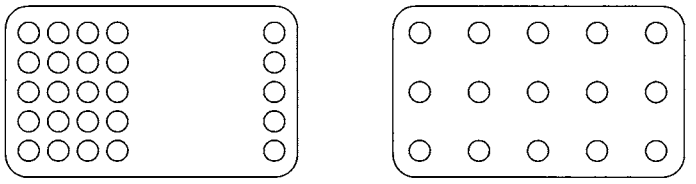


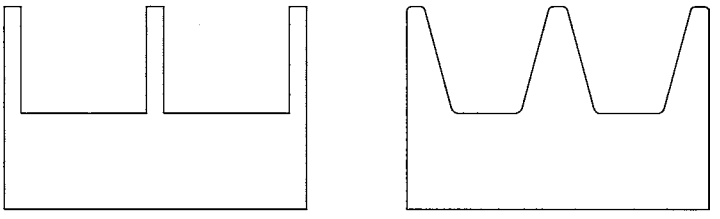
a. Sharp corners and edges (on left) must be rounded as shown on right.



b. Unequally spaced cuts (on left) should be separated, as shown on right.



c. Unequally distributed piercing (on left) should be even.



d. Thin and thick sections (on left) must be avoided.

FIGURE 14-12 Design changes for less distortion in heat treatment.

Wear resistance and hot hardness are other important segments of tooling material suitability. These two properties are somewhat dependent on each other, as tool wear is enhanced with lower hot hardness. Hot hardness of a material is its resistance to softening produced by high operating temperatures. Hot hardness should be greater where the high-speed work and subsequently high-temperature working environment is expected.

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TABLE 14-6 Commonly Used Tooling Materials and Their Qualities

Material	Hardness, Vickers scale	Transverse rupture strength, lb/in.^{2}
High-speed steel	100–1,100	440,000–750,000
Cemented carbides	900–1,800	120,000–400,000
Ceramics	1,700–2,100	73,000–160,000
Cubic boron nitride	4,000–6,000	15,000–29,000
Diamond	8,000–10,000	7,000–20,000

Toughness of materials is the demarcation of their ability to withstand shocks, interruptions of their work path, sudden application of loading, and all abrupt changes without deformation or breakage. The material's elastic limit is important in this evaluation, as such parts should be rigid, not succumbing to deformation be it elastic or plastic, and yet not be brittle or unyielding to break easily in service.

The most common tool materials used today are as shown in Table 14-6. They are grouped according to their hardness and transverse rupture strengths. The two properties are dependent on each other.

The values shown in Table 14-6 are approximate only, presented for comparison. The Vickers hardness denomination shows quite high ranges, considering that 1700 $HV = 78$ *HRc.*

14-4-1 Tool Steel Materials

There is a lot expected from tool steel materials nowadays. With costs being cut everywhere, prices of finished goods being slashed to the bare minimum, and production running on diminishing margins, tooling just should not break or need to be sharpened too often.

Demands are abundant, and so are the choices. Tool steels, which may often accommodate situations almost controversial, are here for the asking. The continuous research of material manufacturers produced results in the form of an emergence of more versatile tool steel materials of either general or narrowly specialized qualities.

Under the sponsorship of AISI and SAE, a classification system for tool steel has been developed, grouping all materials into several categories, shown in Table 14-7.

The quick reference data presented in Table 14-8 should serve as a rough identifier of available tooling materials for a given application. This is a starting point in the evaluation of materials, with a finer distinction to be based on the ratings of their properties, on their availability, cost, economical aspects, and all additional applicable factors. Vital mechanical properties of tooling materials were described at the beginning of this section.

The most often used steel types in the die-building practice are W1, W2, O1, A2, D2, D4, M2, S1, and S5. They represent a majority of selections design engineers make when deciding on the proper tooling material. All these steels may be categorized according to the additives constituting their main properties, according to their applications, or to their method of hardening, and so on. (Table 14-9 through 14-11).

The properties with the greatest impact on the tooling material selection are

- Resistance to softening at high temperatures, or hot hardness
- Depth of hardness penetration during the heat-treating process
- Abrasion and wear resistance

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TABLE 14-7 Classification to Tool Steels

Type of tool steel	AISI letter symbol	Main distinction
High-speed steel	M	Molybdenum content
	T	Tungsten content
Hot-work steel	H1–H19	Chromium content
	H20 and up	Tungsten content
	H40 and up	Molybdenum content
Cold-work steel	D	High carbon and high chromium
	O	Oil-hardening steel
	A	Medium alloy, air hardening
Shock-resisting steel	S	Low carbon content, alloying elements vary with type
Mold steel	P	Very low carbon content
Special-purpose steel	L	Low-alloy
	F	Carbon-tungsten, low-alloy
Water-hardening steel	W	Minimum of alloying elements

14-4-1-1 High-Speed Tool Steels (categorized as M and T). The two groups of high-speed tool steels are based on the content of their main alloying element, which may be either tungsten or molybdenum.

Molybdenum High-Speed Tool Steels (M group). Molybdenum is the main constituent of this group, even though in some combinations certain percentages of other significant elements, such as tungsten and cobalt, may also be present. Steels of a higher than usual carbon content and steels with an additional content of vanadium for increased resistance to abrasion may be found within this group.

TABLE 14-8 Tool Steel Selection Guide

High-speed steel application: Cold and hot dies, roller bearing

M category	For high abrasion areas
T category	Where high hot hardness is needed

Cold-work steel application: Cutting tools for medium speeds, and where heat-treatment stability is required

D category	Cutting, coining, drawing tools, thread rolling dies. Tooling for long runs
O category	Coining tools for medium runs
A category	Bushings, cutting, trimming, forming, and bending tools. Tooling for medium runs

Shock-resisting steel application: Hot work (punching, shearing), cold work. For hobbing, hot swaging, compression molding applications

Special-purpose steel application: Cutting tools and knives, blanking and trimming sets. Used where exceptional toughness is required

Water-hardening steel application: Where high abrasion resistance and hot hardness are needed. Cold-work tooling, such as cutting tools, cold heading dies. Hot-work tooling application, such as drop forging dies. Tooling for short runs

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TABLE 14-9 Tool and Die Steels

AISI steel type*	Nominal composition, %							
	C	Mn	Si	W	Cr	Mo	V	Other
W1	1.00							
W2	1.00						0.25	
O1	0.90	1.00		0.50	0.50			
O2	0.90	1.60						
O6	1.45		1.00			0.25		
A2	1.00				5.00	1.00		
A4	1.00	2.00			1.00	1.00		
A6	0.70	2.00			1.00	1.00		
A7	2.25			1.00	5.25	1.00	4.75	
A8	0.55			1.25	5.00	1.25		
A10	1.35	1.80	1.25			1.50		1.80 Ni
D2	1.50				12.00	1.00		
D3	2.25				12.00			
D4	2.25				12.00	1.00		
D5	1.50				12.00	1.00		3.50 Co
D7	2.35				12.00	1.00	4.00	
S1	0.50			2.50	1.50			
S2	0.50		1.00			0.50		
S4	0.55	0.80	2.00					
S5	0.55	0.80	2.00			0.40		
S7	0.50				3.25	1.40		
T1	0.70			18.00	4.00		1.00	
T15	1.50			12.00	4.00		5.00	5.00 Co
M1	0.80			1.50	4.00	8.00	1.00	
M2	0.85			6.00	4.00	5.00	2.00	
M4	1.30			5.50	4.00	4.50	4.00	
L3	1.00				1.50		0.20	
F2	1.25			3.50				

*W, water-hardening; O, oil-hardening, cold work; A, air-hardening, medium alloy; D, high-carbon high-chromium, cold work; S, shock-resisting; T, tungsten-base, high-speed; M, molybdenum-base, high-speed; L, special-purpose, low-alloy; F, carbon-tungsten, special-purpose.

Source: Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from The McGraw-Hill Companies.

Properties of various molybdenum-based steel types from Table 14-12 and their application are as follows:

AISI M1 steel is a cheaper substitute for the well-known T1 steel group, with molybdenum used in place of tungsten. Properties of both steel types are quite similar, the only difference being greater sensitivity of molybdenum steel to heat treatment. M1 steel's application includes drills, reamers, milling cutters, and lathe cutters for light-duty work.

AISI M2 is similar to M1, with a portion of its molybdenum content replaced by tungsten. It is suitable for general work, displaying improved toughness and wear resistance, while being less problem-prone in hardening and economically more advantageous. It is a good choice of steel for all cutting applications, be it drills, mills, lathe tooling, and so on.

AISI M3 with vanadium added for improving its wear resistance is preferred especially where the property is required. Otherwise it is widely used for broaches, milling cutters, reamers, and so on.

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TABLE 14-10 Recommended Tool Steels for Press Tooling

Application	AISI steel type*	Hardness, Rockwell C
Blanking dies and punches (short runs)	W2	57–65
	O1	58–62
	A2	58–62
Blanking dies and punches (long runs)	A2	58–62
	D2	58–62
	M4	58–62
Bending dies	O1	58–62
	A2	58–62
	D2	58–62
Coining dies	S1	52–55
	W1	58–62
	A2	58–62
	D2	58–62
	D4	58–62
Drawing dies	W1 or W2	58–64
	O1	58–62
	O6	58–62
	A2	58–62
	D2	58–62
	D4	58–62
Dies (cold extrusion)	D2	60–64
	M4	63–65
Dies (embossing)	O1	59–61
	O2	59–61
	A2	59–61
	D2	59–61
Dies (lamination)	M2	58–62
	D2	58–62
	D4	58–62
	M4	60–62
	T15	60–62
	D7	60–62
	A7	60–62
Dies (sizing)	W2	61–64
	M2	61–64
	D2	61–64
	M4	61–64
Dies and punches (trimming)	W2	57–60
	A2	57–60
	D2	57–60
	D4	57–60
	M4	57–60
Punches (embossing)	S1	59–61
	S5	59–61
Punches (trimming)	W2	57–60
	O1	57–60
Punches (notching)	W2	57–60
	M2	57–60

*Several of the other tool steels listed in Table 14-9 are also used for these applications, depending on the preferences, special applications, and heat-treating facilities found in certain plants.

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TABLE 14-11 Comparison of Basic Characteristics of Tool and Die Steels

AISI steel type	Non-deforming properties	Safety in hardening	Toughness	Resistance to softening effect of heat	Wear resistance	Machinability
W1	Low	Fair	Good	Low	Fair	Best
W2	Low	Fair	Good	Low	Fair	Best
O1	Good	Good	Good	Low	Fair	Good
O2	Good	Good	Good	Low	Fair	Good
O6	Good	Good	Good	Low	Fair	Best
A2	Best	Best	Fair	Fair	Good	Fair
A4	Best	Best	Fair	Fair	Good	Fair
A6	Best	Best	Fair	Fair	Good	Fair
A7	Best	Best	Low	Fair	Best	Very low
A8	Good	Best	Best	Good	Good	Fair
A10	Best	Best	Fair	Fair	Good	Good
D2	Best	Best	Low	Fair	Very good	Low
D3	Good	Best	Low	Fair	Very good	Low
D4	Best	Best	Low	Fair	Very good	Low
D5	Best	Best	Low	Fair	Very good	Low
D7	Best	Best	Low	Fair	Best	Very low
S1	Fair	Good	Best	Fair	Fair	Fair
S2	Fair	Good	Best	Fair	Low	Fair
S4	Fair	Good	Best	Fair	Low	Fair
S5	Fair	Good	Best	Fair	Low	Fair
S7	Fair	Good	Best	Fair	Good	Fair
T1	Good	Good	Good	Best	Very good	Fair
T15	Good	Good	Low	Best	Best	Very low
M1	Good	Good	Good	Best	Very good	Fair
M2	Good	Good	Good	Best	Very good	Fair
M4	Good	Good	Good	Best	Very good	Fair
L3	Fair	Good	Good	Low	Fair	Good
F2	Fair	Fair	Low	Low	Good	Fair

Source: Frank W. Wilson, *Die Design Handbook,* New York, 1965. Reprinted with permission from The McGraw-Hill companies.

TABLE 14-12 Molybdenum High-Speed Tool Steels

	M1 through M3	M4	M7 through M10	M30 and up
Depth of hardening	5	5	5	5
Decarburization resistance	3–4	4	3	3
Safety in hardening	2	2	2	2
Shape stability in heat treatment (air)	3	3	3	3
Shape stability in heat treatment (oil)	2	2	2	2
Machinability	1–2	2	2	2
Wear resistance	4	5	4	4
Toughness	1	1	1	1
Hot hardness	4	4	4	5

Relative evaluation, where 1 is the lowest rating and 5 is the greatest.

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AISI M7 has a higher carbon and vanadium content, which readily raises its cutting efficiency but without lowering its toughness. Otherwise M7 steel is similar to M1. Greater care should be exercised in heat treatment, where a salt bath or a controlled atmosphere is recommended because of the material's proneness to decarburization. Applications include blanking and trimming dies, shear blades, thread rolling dies, and lathe tooling.

AISI M10 has excellent wear resistance owing to its higher vanadium content. Various cutters and lathe tooling are made from this type of steel, with usage for blanking dies and punches, shear blades, and similar.

AISI M42 has good hot hardness as well as regular hardness produced by the addition of cobalt. Forming tools, fly cutters, thread rolling dies, tool bits, shaving tools, and similar tools may be made from this type of material. All M40 group members are also utilized for tooling on materials with a low machinability index.

Tungsten High-Speed Tool Steels (T group). These materials are irreplaceable where a high-temperature working environment is encountered. They are also more permissible in heat treatment, having a distinct resistance to decarburization while not being excessively prone to distortion.

Properties of tungsten-based steels from Table 14-13 and their applications are as follows:

AISI T1 is also known as the 18-4-1 type of steel; its designation refers to the percentages of the primary alloying elements: W-Cr-V. A high toughness, combined with better machinability and permissibility in heat treatment, makes this type of steel an excellent general-purpose material. It is used in all multiflute cutters, threading taps and dies, machine knives, lathe tooling, and punches and dies.

AISI T2 is a very agreeable material with regard to machining and heat treatment, where it is comparable to T1 material, in spite of its higher carbon content and twice the percentage of vanadium. Because of its improved wear resistance, T2 is chosen where finer and more precise cutting is needed. It is an excellent choice for all finishing tools and forming inserts. Generally it may be used in all situations where T1 steel would be selected.

AISI T5 has a higher cobalt and vanadium content, the combination of which produces excellent wear resistance combined with a very high hot hardness. Its tendency to decarburization should be controlled in heat treatment, utilizing a slightly reducing atmosphere. This steel may be recommended for all single-fluted tooling, for high speeds and feeds, for cutting of materials with lower machinability index, and for removal of larger chunks of material.

TABLE 14-13 Tungsten High-Speed Tool Steels

	T1,T2	T4	T5,T6	T8,T15
Depth of hardening	5	5	5	5
Decarburization resistance	5	4	3	4
Safety in hardening	3	2	2	2
Shape stability in heat treatment (air)	3	3	3	3
Shape stability in heat treatment (oil)	2	2	2	2
Machinability	2	2	1–2	1–2
Wear resistance	4	4	4	4–5
Toughness	1	1	1	1
Hot hardness	4	5	5	5

Relative evaluation, where 1 is the lowest rating and 5 is the greatest.

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AISI T15 boasts excellent wear resistance and unsurpassed cutting ability, along with increased hot hardness. The higher vanadium content, aided by a very high percentage of carbon and some cobalt, produces a steel of the best working qualities within the high-speed steel group. As a permissible material in heat treatment, T15 steel can withstand quite high heat-treating temperatures, followed usually by more than one tempering pass. The machinability index of this material is very high, even though its grindability suffers. Because of its lower toughness, it may not be used where greater shock resistance is required. Otherwise its applications include cold-work tooling such as dies and punches, either blanking or forming.

14-4-1-2 Hot- or Cold-Work Steels (categorized as H, D, O, and A). Another distinction within tool steel materials divides them into hot- and cold-working.

Hot-work tool steels, including all H-type materials, are not described here since their application range covers mostly the mold-building branch of industry, even though some marginal uses within the field of stamping dies may certainly be found.

Cold-work tool steels can be grouped into three major categories: (1) high-carbon, high-chromium type steels, (2) oil-hardening cold-work tool steels, and (3) medium-alloy, air-hardening, cold-work tool steels. A list of selected properties is enclosed in Table 14-14.

1. **High-carbon, high-chromium, cold-work tool steels (D group)** were mainly intended for die work, even though other general applications may be found.

   AISI D2 is an air-hardening die steel, high in hardness, abrasion resistance, and resistance to deformation. Its machinability is quite good and may still be improved by a slightly greater amount of sulfur within the material makeup. Well-dispersed particles of sulfide considerably improve the material's machinability and surface finish. Heat treating to a lower hardness positively affects the material's toughness. D2 steel is frequently used for making all types of dies, be it cutting dies, forging dies, or other die-related tooling.

   AISI D3 oil-hardened steel offers excellent resistance to abrasion and wear. It is immune to deformation and displays a superior compressive strength under a gradually increasing load. Its deep-hardening properties make it an excellent choice where frequent regrinding of tools is necessary. Otherwise it is utilized for blanking and other cutting punches and dies intended for long production runs, and it is recommended wherever a high resistance to wear is required.

2. **Oil-hardening, cold-work tool steels (O group)** contain a significant amount of manganese, but the percentage of other alloying elements is quite low. This inexpensive tool steel does not resist wear and deformation, but the depth of its hardness penetration is impressive. A good machinability index makes this type of steel a good choice where short runs of parts are produced.

TABLE 14-14 Cold-Work Tool Steels

	D2	D3	D4, D5	O1, O2	O6	A2,A3	A6
Depth of hardening	5	5	5	4	4	5	5
Decarburization resistance	4	4	4	5	5	4	5
Safety in hardening	5	3	5	4	4	5	5
Shape stability in heat treatment	5	4	5	4	4	5	5
Machinability	1	1	1	3	4	2	1
Wear resistance	4	4	3–4	2	2	3–4	2
Toughness	1	1	1	2	2	2	2
Hot hardness	3	3	3	1	1	3	2

Relative evaluation, where 1 is the lowest rating and 5 is the greatest.

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AISI 01 steel has a minimal tendency to warpage and shrinking during the heat-treating process, but its resistance to high heat is not commendable. It is often used for slow-running cutting tools such as taps, drills, and reamers, and for all cutting and forming die tooling for short or medium production runs.

AISI 02 also displays nondeforming properties of the previous type, coupled with an ease of machining, good wear resistance, and safety in hardening at low temperatures. It is mainly used for cutting tools of low- and medium-speed ranges, for making of thread rolling dies, forming tools, bushings, and gauges.

AISI 06 is a graphitic type of steel, owing to small particles of graphitic carbon equally dispersed throughout its content. Approximately one-third of the total percentage of carbon is present in the form of free nodular graphites which supplement ease of machining. Parts made from this type of steel often utilize these free graphites as a sort of lubricant, with subsequent reduction in wear and galling. O6 steel presents no problems in hardening, utilizing quite low quenching temperatures while attaining a deep-hardness penetration with almost no dimensional change. This steel is most often used for bushings, for holders of tool cutter's inserts, for shanks of cutting tools, for arbors, jigs, gauges, cutting and forming punches and dies, and where stability of the material is of greater importance than its wear resistance.

3. **Medium-alloy, air-hardening, cold-work tool steels (A group)** have a high machinability index accompanied by high toughness and nondeformity in heat treatment. Even though the alloy content is low, hardening by air quenching is acceptable. However, wear resistance of these materials is not impressive.

AISI A2 alloy has a low chromium content that places it within a competitively priced range of steels, with its resistance to deformation equal to that of high-chromium materials. An inclusion of sulfur improves the machinability, while a reduced wear resistance is balanced by an increased toughness. This type of steel is most often used for punches and dies, either cutting or forming, for cold and hot trimming dies, and for thread rolling dies.

AISI A6 may be air hardened from a low temperature, which makes this steel comparable to oil-hardening types, with an additional advantage of improved stability in the heat-treating process. Its main usage is within the die-building field as forming tools, gauges, and tooling that does not need a high degree of wear resistance.

14-4-1-3 Shock-Resisting, Mold, and Special-Purpose Tool Steels (categorized as S, P, L, and F). Each of these steel types was originally developed for quite a specific use, but gradually they all advanced into additional fields of application.

Shock-Resisting Steels (S group). These are steels of increased toughness, even though suffering from lowered wear resistance (Table 14-15). Their carbon content is

TABLE 14-15 Shock-Resistant and Special-Purpose Tool Steels

	S1	S2	S5	L2	L6	F2
Depth of hardening	4	4	4	4	4	3
Decarburization resistance	4	3	3	5	5	5
Safety in hardening	3	1	3	2	3	1
Shape stability in heat treatment	2	1	2	1–2	3	1
Machinability	2	2	2	3	2	2
Wear resistance	1–2	1–2	1–2	1	2	3–4
Toughness	4	5	5	4	4	1
Hot hardness	2	1	1	1	1	1

Relative evaluation, where 1 is the lowest rating and 5 is the greatest.

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quite low, and their alloying elements vary with each steel's composition. The diversification in alloying additives produces different properties, such as hot hardness, machinability, and abrasion resistance.

AISI S1 is a chromium-tungsten alloy, demonstrating in its hardened condition a great toughness, with considerable strength and hardness. The influence of low carbon content on the wear resistance of this material may be alleviated by carburizing, which will not diminish its generous shock-resisting qualities. Main uses are for piercing and forming tools, drop forging die inserts, heavy shear blades, tooling for shock loads, and the like.

AISI S2, with its moderate wear resistance, presents good resistance to rupturing. It is mainly used in the manufacture of pneumatic tools, hand chisels, and a limited amount of hot work. For this last application it must be heat-treated in a neutral atmosphere in order to avoid either carburization or decarburization of its surface.

AISI S5 is a silicon-manganese steel with some chromium, vanadium, and molybdenum added to obtain an improvement in the depth of hardness penetration and a refinement of the inner grain structure. These steels are quenched in oil, although a water quench may also be used where the shape of a part does not contain sharp corners, drastic deviations in thickness, and other designing faults. High elastic limit and good ductility are among the most sought after properties of this type. The material is used for heavy-duty punches, bending rolls, shear blades, and also for shanks of carbide tools and machine parts that are subject to shock.

Mold Steels (P group). These steels have a quite low carbon content, in which they differ from other types of tool steels. They therefore require carburizing, while their high resistance to decarburization protects them from the reversal of this process. Their dimensional stability is very good, accompanied by an excellent surface finish and the possibility of altering their shape by hobbing instead of regular machining. These steels are mostly used in mold-making.

Special-Purpose Tool Steels (L and F group). These low-alloyed steels have various properties, often even conflicting ones. These materials are cheaper than higher-alloyed tool steels.

AISI L6 is resistant to deformation, and its toughness is quite good in comparison with that of other oil-hardening types of steel. The alloy content and abrasion resistance is low. This tool steel material is recommended for use where moderate shock and wear resistance are required, as in forming and trimming dies, knuckle pins, clutch members, and the like.

AISI F2 is a carbon-tungsten type of material, sensitive to thermal variations, even to heat treatment, during which it may succumb to distortions. Such a tendency, along with its low resistance to cracking during the hardening process, makes the application limited to tools of simple shapes. Hardening must be very shallow, yet it produces a tough core. Regardless of all drawbacks, this type of material is quite resistant to abrasion.

14-4-1-4 Water-Hardening Tool Steels (categorized as W). These steels contain a minimum of alloying elements, with their carbon content varying from group to group. Quenching should be harsh, utilizing water or brine. Where the carbon content is higher, such steel is more sensitive to emergence of defects due to heat treatment. Steels of this type are then used for more demanding applications. Table 14-16 rates their characteristics.

Water-Hardening Steel Type W-1 (Plain Carbon). Group I, with carbon content between 0.7 and 0.9 percent, is tough and may be used where shock or harsh treatment is expected. Applications include cold punches, fixture elements, anvil faces, chuck jaws, screwdriver blades, chisels, and so on.

Group II, of carbon content 0.9 to 1.1 percent, has a moderate ability to withstand shock, which is accompanied by greater hardness and quite satisfactory toughness. It is used for manufacture of hand tools, threading dies, wood augers, die parts for drawing and heading dies, drill bushings, lathe centers, collets, and fixturing elements.

Group III (1.05 to 1.20 percent C) has improved hardness penetration and a good resistance to shock application. Its toughness is reduced, but the wear resistance and cutting

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TABLE 14-16 Water-Hardening Tool Steels

	All grades
Depth of hardening	3
Decarburization resistance	5
Safety in hardening	2
Shape stability in heat treatment	1
Machinability	5
Wear resistance	1
Toughness	2–3
Hot hardness	1

Relative evaluation, where 1 is the lowest rating and 5 is the greatest.

ability is high. It is used for hand tools, such as knives, chisels, slow-running cutting tools, center drills, and parts of blanking, bending, and coining dies.

Group IV (1.2 to 1.3 percent C) may be case hardened to a greater depth. This steel has improved wear and abrasion resistance, offset by a sensitivity to shock loads and to application of concentrated stresses. Often this type of material is used for finishing cutters and forming and burnishing tools.

14-4-2 Cemented Carbides

Prior to the practical and widespread use of cemented carbides, which began in the thirties, cutting tool materials depended mainly on heat treatment to obtain properties needed for machining. At higher speeds, accompanied by higher temperatures, these tools were subjected to the effects of yet another heat treatment, the one that subsequently ruined them.

Not too many materials even today can take the heat produced by a work cycle without being affected by its detrimental influence. Aside from ceramics, cemented carbides are probably the only additional tooling material. Made from a mixture of carbide and an iron filler with cobalt, they are compacted and sintered. They display superior hardness even at higher temperatures, for which property they can be used where higher machining speeds are necessary or where machining of harder materials has to be done. Cemented carbides come in several forms. The most common types are tungsten carbides and titanium carbides.

14-4-2-1 Tungsten Carbides. These may further be subdivided into two groups: (1) Two-phase-type tungsten carbide with a cobalt binder (WC-Co), which is the most commonly used type. It displays an extreme hardness and resistance to abrasion, which predisposes it to be used where wear by abrasion is expected. (2) Alloyed tungsten carbide, alloyed with either titanium carbide (TiC) or tantalum carbide (TaC) or both, which should be used where wear of tooling by cratering is possible.

Cobalt in tungsten carbide tooling increases its strength; however, in greater quantities it lowers the wear resistance, hot hardness, cratering resistance and resistance to deformation due to higher temperatures. The addition of titanium carbide works oppositely: It increases the wear resistance, hot hardness, cratering resistance, and tendency to deformation at higher temperatures of the material, but it decreases its strength. Tantalum carbide in tungsten carbide material decreases the strength and wear resistance while increasing the resistance to deformation caused by the material's exposure to high temperatures.

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Depending on the cobalt content, tungsten carbide's Rockwell A hardness is very high and may range between A89 and A94.

14-4-2-2 Titanium Carbides. These are usually made of a titanium carbide combination with additional nickel and molybdenum (TiC-Ni-Mo). The Rockwell A hardness ranges of commercial grades are between 92 and 93, and they are recommended only for high-speed precision machining or finishing operations at higher speeds and lower cutting feeds and depths. Titanium carbides display a superior strength and can operate at high-speed rates, of up to 1500 surface ft/min. They produce a superior surface finish, for they have no tendency to adhere to the workpiece material. An exception to this is their use with aluminum-based materials, which produce no satisfactory results. Because of their excellent flank wear resistance, they can be used to attain high-tolerance-range work.

14-4-3 Ceramics

Ceramic tools are brittle, but their hardness and durability are admirable. They retain their high range of hardness even at extreme temperatures of 1400°F, at which the hot hardness of all other tooling fails. Ceramics are therefore excellent for all machining work which requires a good surface finish or for machining of already hardened parts (up to Rockwell C 65). Ceramic tooling does not produce a welding tendency between the workpiece and the tool, as it generates less heat during the machining process than, for example, carbide tooling. Their main source of wear is oxidation.

Ceramic materials are most often based on aluminum oxide (Al_2O_3) but with some marginal utilization of zirconium oxide (ZrO_2) or magnesium oxide (MgO) and even nonoxides such as silicon nitride (Si_3N_4) or silicon carbide (SiC). The internal structure of ceramics is very dense yet porous. Because of their low transverse rupture strength, they should not be used where interrupted cuts are to be produced. They are also quite sensitive to notches, which become stress-concentrating points, fracturing the material under quite a low tension.

The low ductility of the material, resulting in its brittleness, often renders ceramics unreasonable to use in some applications. Also their low tensile strength, which makes them susceptible to ruptures and failures due to minute chipping, may be quite restrictive. To enhance their tensile qualities, ceramic materials must be kept under compression. Further, they should never be exposed to bending, twisting, or pulling influences. Heavy cuts are also not recommended for this type of tooling. But the advantage of their excellent wear resistance combined with low thermal conductivity (half of that of carbide tooling) often outweighs their drawbacks. They are irreplaceable where higher cutting speeds and their variations are needed, for wide, facing cuts, or for cutting of highly abrasive materials. Tables 14-17 through 14-19 give cutting speeds, a troubleshooting guide, and selected properties of ceramic materials.

The tool life of ceramics can be lowered by an increase in cutting feed or speed. This is caused by an increase in temperature, which will—in turn—negatively affect the wear mechanism of the tooling. Wear resistance of ceramics is improved with the formation of interfacial residual compounds such as aluminate formation on alumina tooling material or silicate layers on SiAlON. These protective layers begin to form on the surface of tooling during work cycles conducted at higher cutting speeds, and such coating produces more protection from wear than the basic material from which it evolved.

It is speculated that the formation of these protective layers is facilitated by a low thermal conductivity of ceramics in general, which at high cutting speeds suffers from the localized overheating of the cutting edge. The formation of a protective layer is therefore a subsequent reaction to such thermal abuse of the material.

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TABLE 14-17 Recommended Cutting Speeds for Ceramic Cutting Tools by Material Classification

Material to be machined	Material condition or type	Roughing (over 1/16 in depth, 0.015 to 0.030 in feed)	Finishing (under 1/16 in depth, under 0.010 in feed)	Recommended tool geometry (rake angles)	Coolant
Carbon and tool steels	Annealed	300–1,500	600–2,000	Negative	
	Heat-treated	300–1,000	500–1,200	Negative	N.R.*
	Scale	300–800		Negative with edge hone	
Alloy steels	Annealed	300–800	400–1,400	Negative	
	Heat-treated	300–800	300–1,000	Negative with edge hone	N.R.
	Scale	300–600		Negative with edge hone	
High-speed steel	Annealed	100–800	100–1,000	Negative	
	Heat-treated	100–600	100–600	Negative with edge hone	N.R.
	Scale	100–600		Negative with edge hone	
Stainless steel	300 series	300–1,000	400–1,200	Positive and negative	Sulfur-base oil
	400 series	300–1,000	400–1,200	Negative	
Cast iron	Gray iron	200–800	200–2,000	Positive and negative	
	Pearlitic	200–800	200–2,000	Negative	
	Ductile	200–600	200–1,400	Negative	N.R.
	Chilled	100–600	200–1,400	Negative with edge hone	
Copper and alloys	Pure	400–800	600–1,400	Positive and negative	Mist coolant
	Brass	400–800	600–1,200	Positive and negative	Mist coolant
	Bronze	150–800	150–1,000	Positive and negative	Mist coolant
Aluminum alloys†		400–20,000	600–3,000	Positive	N.R.
Magnesium alloys		800–10,000	800–10,000	Positive	N.R.
Nonmetallics	Green ceramics	300–600	500–1,000	Positive	
	Rubber	300–1,000	400–1,200	Positive	N.R.
	Carbon	400–1,000	600–2,000	Positive	N.R.
Plastics		300–1,000	400–2,000	Positive	N.R.

*N.R., coolant is not required. If a coolant must be used, it is recommended that the tool be flooded to eliminate the possibility of heat checking.
†On certain aluminum alloys, ceramic tools have the tendency to develop a built-up edge.
Source: Haldon J. Swinehart, *Cutting Tool Material Selection*. Reprinted with permission from the Society of Manufacturing Engineers, formerly ASTME, Dearborn, MI.

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TABLE 14-18 Troubleshooting Guide for Ceramic Tools

Problem	Possible causes
Chipping	Lack of rigidity. "Sawtoothed" or too keen a cutting edge. Chip breaker too narrow or too deep. Chatter. Scale or inclusions. Improper grinding. Too much relief. Defective tool holder
Cracking or breaking	Insert surfaces not flat. Insert not seated solidly. Stopping workpiece while tool is engaged. Worn on chipped cutting edges. Feed is too heavy. Improperly applied coolant. Too much rake or relief. Too much overhand or tool too small. Lack of rigidity in setup. Speed too slow. Too much variation in cut for size of the tool. Chatter. Grinding cracks
Chatter	Tool not on center. Insufficient relief and/or clearance. Too much rake. Too much overhand or tool too small. Nose radius too large. Feed too heavy. Lack of rigidity. Insufficient horsepower or slipping clutch
Torn finish	Lack of rigidity. Dull tool. Speed too slow. Chip breaker too narrow or too deep. Improper grinding
Wear	Speed too high or feed too light. Nose radius too large. Improper grinding
Cratering	Chip breaker set too tight. Nose radius too large. Side cutting edge angle too great

Source: Haldon J. Swinehart, *Cutting Tool Material Selection*. Reprinted with permission from the Society of Manufacturing Engineers, formerly ASTME, Dearborn, MI.

14-4-4 Diamond Tooling

Diamond is the hardest natural material, with a resistance to scratching five times greater than that of carbides. Properly utilized, diamond tooling can produce 30 to 300 percent more parts than carbides are capable of turning out between resharpenings.

Diamond crystal is the crystalline form of carbon, very efficient at cutting of nonferrous materials, including aluminum, phenolics and other plastics, graphite, sintered carbides, or fiberglass-filled materials. Because of the smoothness of its surface, chips do not adhere to such tooling even when machining nonferrous materials. Diamond tooling is not recommended for cutting of alloy steels, ferrous metals, and similar harder materials or where a large amount of material is to be removed at once.

Diamond tooling is brittle and should be protected from all shock, be it in the form of machine vibrations or that created by a sudden contact with the machined part. Diamonds are also sensitive to higher heat conditions, which may cause them to crack. They operate well at the highest speeds and feeds, with up to 6000 surface ft/min and 0.001 in. per revolution.

14-5 TYPES OF STEEL AND ALLOYS: PROPERTIES AND CLASSIFICATIONS

Various types of standard steels, as used in metal-stamping practice and other applications, have been grouped according to SAE steel specifications. A numeral descriptive system designates values to specific places within the material code, which provides information about the material's manufacture, type, and carbon and major alloy content.

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TABLE 14-19 Selected Properties of Ceramic Materials

Material	Chemical symbol	Density, g/cm^3	Hardness, Rockwell A scale	Hardness, Vickers	Modulus of elasticity $\times 10^6$ lb/in.^{2} (in tension)	Thermal conductivity W/m/K at 25°C	Coefficient of linear thermal expansion, $\times 10^{-6}$/K at 25°C
Alumina	Al_2O_3	3.9–4.0	93–95	1000–2400		30.0	6.5–7.0
Aluminum nitride	AlN	3.26		200		2.7	
Silicon nitride	Si_3N_4	3.1–3.3	86–95	1800–2000	20–32	15–25	2.7–3.5
Silicon carbide	SiC	2.6–3.3			35–58	20–95	3.5–4.5
Tungsten carbide	WC	15.7		1400–1800	105	22	5.2
Titanium carbide	TiC	5.0		1700	47	21	7.4
Titanium nitride	TiN	5.4	92		38	30	9.35
Tantalum carbide	TaC	14.5		1800	42	22	6.3
Magnesium oxide	MgO	3.6				53	
Zirconia	ZrO_2	5.7–6.1	91–94	1600–2200	29	1.8–2.2	9.0–11.0
Diamonite	Cr_2O_3	4.15				22	8.0

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14-5-1 Standard Grades of Steel

The basic code system for these materials is as follows:

_10XX

A prefix A, B, C, D, E may be added in front of the coded description of the material. The meanings of different AISI prefix letters are:

A - Basic open-hearth steel

B - Acid bessemer carbon steel

C - Basic open-hearth carbon steel

D - Acid open-hearth carbon steel

E - Electric furnace steel

The first numeral, shown above as 1, describes the type of steel or its major alloying element. The numerals and their meanings are listed as follows:

1 - Carbon steel

2 - Nickel steel

3 - Nickel-chromium steel

4 - Molybdenum steel

5 - Chromium steel

6 - Chromium-vanadium steel

8 - Triple-alloy steel

9 - Silicon-manganese steel

The last two (sometimes three) numbers of the material code give the content of carbon within the material. For example, 1050 steel has a carbon content of 0.5 percent.

Typical mechanical properties of selected carbon and alloy steels are given in Table 14-20. A brief description and comparison of various steel types according to their common qualities and drawbacks is included below.

Carbon steels, SAE 1006 through 1015, are steels with the lowest carbon content, as their numbers indicate. They have low tensile strengths and may be obtained in variations of (1) rimmed steels of deep drawing qualities and (2) killed steels of nonaging tendencies. Steels within this range are susceptible to grain growth due to the amount of cold working, which produces brittleness of the material. Welding of these materials presents no difficulties, while their free machining qualities are impaired. A cold-drawing process may improve the machinability. Yet these steels should not be used for parts where broaching or turning is required and better surface finish is to be produced. The best application of this type of material includes car body covers, oil pans and other deep-drawn parts (rimmed steel), and intricate stampings (killed steel).

SAE 1017 through 1027 steels are the carburizing or case-hardening grades, with an increase in their hardness and strength and lowered cold-forming properties. A greater carbon content and an inclusion of manganese raise their depth of hardness penetration while improving the hardness of the core. An increased manganese content aids the machinability, whereas lowered manganese aids the formability. For a greater uniformity of heat treatment, killed steel should be used. Brazing and welding of these materials poses no problems. Their uses include frames, fan blades, welded tubing (1020), and bolts of low strength.

SAE 1030 through 1052 steels are medium-carbon materials, heat-treatable, with a possibility of selective hardening (flame or induction hardening), useful for cold work and where their higher mechanical properties are required. They are used as forgings for parts

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TABLE 14-20 Properties of Selected Steel Materials

Material	Mfg. process	Tensile strength, KSI	Yield strength, KSI	Elongation, % in 2 in.	Reduction of area, %	Hardness, Brinell
1018	Hot rolled	58	32	25	50	115
	Cold drawn	64	54	15	40	125
1020	Hot rolled	55	30	25	50	110
1030	Hot rolled	80	50	32	57	180
	Normalized	75	50	32	60	150
1035	Hot rolled	72	40	18	40	144
	Tempered	103	72	23	59	200
1040	Hot rolled	90	60	25	50	200
	Normalized	85–86	54	28	55	170
1045	Hot rolled	82	45	16	40	162
	Cold drawn	91	77	12	35	178
1095	Hot rolled	120	66	10	25	245
	Tempered	200	137	12	37	385
1137	Hot rolled	91	55	28	61	190
	Normalized	97	57–58	22	48	196
1141	Hot rolled	94	50–51	15	35	186
	Cold drawn	105	88	10	30	210
1340	Annealed	102	63	25	57	207
4130	Hot rolled	90	52	28		178
4150	Annealed	106	55	20	40	196
	Normalized	167	106	12	31	320
4340	Annealed	100	58	21	45	230
	Normalized	185	125	12	36	360
5150	Annealed	98	50	22	43	195
	Normalized	125	75	20	59	254
6150	Annealed	97	55	23	45	195
	Normalized	135	88	22	61	270
8630	Annealed	81	54	29	59	155

like truck front axles and tractor and automobile components. A proper heat treatment of these products is necessary for their machinability. Another use is bar stock for machining, with or without heat treatment. Where utilized for stampings, flat parts or parts with only simple bends are recommended.

SAE 1055 through 1095 steels boast a high carbon content, greater than necessary for attainment of maximum hardness. The higher carbon content makes these materials suitable for manufacture of coiled springs or cutting tools, with the necessity of heat treatment after machining. Their cold-forming properties are extremely limited, and metal-stamping applications are reserved for flat parts, such as washers. Most use is for farming machinery.

SAE 1111, 1112, 1113 steels, or free-cutting steels, are easily machinable, in return for their poor cold forming, welding, and forging characteristics. Their machinability improves with a higher sulfur content. They are also known as bessemer screw stock.

SAE 1109 through 1126 steels combine a good response to heat treatment with good machining properties. Grades with lower carbon content are used for parts to be cyanided or carbonitrided. Steels with greater manganese content have better hardenability tendencies.

SAE 1132 through 1151 steels are specified for various machining purposes, as they are frequently used for manufacture of threaded nuts, bolts, and studs. Greater manganese content of some steels aids their hardenability.

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14-5-2 Stainless Steels

Stainless steels are iron-base alloys containing 10.5 percent or more chromium in their composition. Such a high chromium content provides resistance to corrosion by forming a thin and transparent film of chromium oxide over their surface. Properties of this protective coating are quite amazing: If such a layer is disrupted or ruined, a new surface layer emerges in its stead. The functionability of this surface protection is applicable to all normal atmospheric conditions, including exposure to humidity and weathering. It further expands in the form of resistance to various chemical influences, which are usually limited to a certain group of specific steel type. Such applications are listed in every steelmaker's catalog.

A further improvement in surface protection may be achieved by including additional amounts of chromium, as combined with nickel, molybdenum, and similarly acting alloying elements.

In secluded areas, if the protective layer of chromium oxide is disrupted, pitting of the material surface may occur. Where such a possibility is expected, the choice of stainless-steel grade should be 316 or 317 where a higher molybdenum content prevents such defects.

However, corrosion may at times affect stainless-steel materials in its intergranular form. This may happen where the material is heated to 800 to 1650°F and then cooled. During this stage, the chromium content of the layers closest to the surface may combine with carbon to form chromium carbides. This reaction, called carbide precipitation, or sensitization, directly influences the appearance of intergranular corrosion and its magnitude.

To prevent such corrosion, stainless steels specified for high-heat applications like welding should be limited to materials with carbon levels under 0.03 percent. Also a selection of stabilized types, such as type 321, which is stabilized with titanium, or type 347, stabilized with columbium, is recommended.

Where intergranular corrosion cannot be averted, parts may be annealed to dissolve the carbides tied up in the chromium carbide formations.

14-5-2-1 Types of Stainless Steel. The AISI numbering system is used to categorize all stainless-steel materials within three categories:

Austenitic Stainless Steels. These are AISI types 201, 202, 205, 301 through 305, 308 through 310, 314, 316, 317, 321, 329, 330, 347, 348, and 384. The austenitic stainless steel may be strengthened by cold working, while retaining a good ductility and toughness, but they cannot be hardened through heat treatment. A sample hardness of 201 and 301 type of stainless steels is as follows:

	Minimum tensile strength, lb/in.^{2}	Minimum yield strength, lb/in.^{2}
¼ hard	125,000	75,000
½ hard	150,000	110,000
¾ hard	175,000	135,000
Full hard	185,000	140,000

Physical properties of austenitic stainless steels are comparable to those of ferritic and martensitic grades.

Ferritic Stainless Steels. These contain AISI types 405, 409, 429, 430, 434, 436, 442, and 446. In the annealed condition, their toughness decreases simultaneously with the increase of their chromium content. Ferritic stainless steels have 12 percent or more of chromium in their composition. Their ductility tends to be elevated by the inclusion of additional molybdenum, while greater carbon content tends to decrease this property. Exposure to heat, such as that produced by welding, causes enlargement of the grain size, which in turn decreases the material's mechanical properties.

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Ferritic stainless steels are used in the automotive industry, for kitchen utensils and equipment, and as appliance parts, fasteners, and various other machined components.

Martensitic Stainless Steels. These include AISI types 403, 410, 414, 416, 420, 422, 431, and 440. They are called martensitic steels because when they are heated above the critical temperature of 1600°F and cooled rather rapidly, their metallurgical structure turns into martensite. A stress-relieving treatment or tempering is required for these materials to attain the necessary ductility, impact strength, and corrosion resistance.

The hardness range of martensitic stainless steels in their annealed state is approximately 24 Rockwell C. When hardened, they can be divided into two groups: (1) low-carbon steels, with maximum hardness of 45 Rockwell C; and (2) high-carbon steels, with maximum hardness of 60 Rockwell C. Their hardness, however, increases along with their toughness, for which reason nickel is used to enhance the toughness. Nickel also improves their notch impact strength and corrosion and wear resistance, for it permits a higher chromium content within the material.

Martensitic steels have considerable abrasion and wear resistance and lower modulus of elasticity, but they tend to suffer from temper brittleness if heat-treated within the range of 800 to 1050°F. Properties of stainless steels are listed in Table 14-21.

14-5-2-2 Surface Finish of Stainless Steel. The standard mechanical finish may be divided into two groups: rolled finish (not polished) and polished finish. *Rolled finish* contains categories 1, 2D, and 2B. Groups 1 and 2D are dull in appearance, while the third group, 2B, is bright, as this annealed and descaled material is given a final run through the polished rolls.

Polished finish contains groups 3, 4, 6, 7, and 8. Groups 3 and 4 are obtained by finishing the stock with 100-grit or 150-grit abrasives. No. 6 finish is a satin finish, with a lowered reflectivity. No. 7 finish is highly reflective, obtained by buffing. But the most reflective surface finish is no. 8, which is obtained through polishing with fine abrasive elements and buffing as well.

14-5-3 Aluminum

Grading of aluminum alloys uses a methodology similar to that used for other groups of materials. The first digit identifies the type of alloy. The second digit shows its modification, and the third and fourth digits are reserved for demarcation of aluminum's purity within the given alloy.

The first digit of the alloy designation distinguishes between following types of aluminum alloys, grouped according to their second main constituent to the basic aluminum:

1 - Aluminum, 99 percent minimum and up

2 - Copper

3 - Manganese

4 - Silicon

5 - Magnesium

6 - Magnesium and silicon

7 - Zinc

8 - Other elements

9 - Not used

Where X precedes the four digits' code, for example, X8280, the aluminum alloy is experimental.

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TABLE 14-21 Properties of Stainless Steel

Material type	201	302	303	304	304L	309
Structure of material	Austenitic	Austenitic	Austenitic	Austenitic	Austenitic	Austenitic
Hardening properties	Nonhardening	Nonhardening	Nonhardening	Nonhardening	Nonhardening	Nonhardening
Tensile strength, lb/in.$^2 \times 10^3$	95–115	90	90	85	80	90–100
Yield strength, lb/in.$^2 \times 10^3$	45–55	40	35–40	35	30	35–45
Elongation, %, 2 in.	40–55	50–55	50	55	55	45
Reduction of area, %	40	60–70	55	70	70	65
Modulus of elasticity, in tension, lb/in.$^2 \times 10^6$		28	28–29	29	29	29
Hardness, Brinell	179	150	160 min	180 max	180 max	200 max
Hardness, Rockwell	B90	B85	B80 min	B80–90	B90 max	B95 max
Magnetic permeability at 200 H, annealed	1.02	1.02	1.02	1.02	1.02	1.02
Electrical resistivity, μΩ, cm at 68°F	69.0	72.0	72.0	72.0	72.0	78.0
Heat resistance, max. °F, intermittent service	1500	1450	1450	1600	1600	1800
Machinability index, %	45	50	70	50	50	40–45
Drawability, stamping	Good	Good	Fair	Good	Good	Good
Weldability	Excellent	Excellent	Limited	Excellent	Excellent	Good
Approximate price range, %	45	25	50	50	55	70–75
Carbon (C), %	0.15	0.15	0.15	0.08	0.03	0.20
Manganese (Mn), %	5.5–7.5	2.0	2.0	2.0	2.0	2.0
Silicon (Si), %	1.0	1.0	1.0	1.0	1.0	1.0
Chromium (Cr), %	16–18	17–19	17–19	18–20	18–20	22–24
Nickel (Ni), %	3.5–5.5	8–10	8–10	8–10.5	8–12	12–25
Other elements, %	0.25 N					

(*Continued*)

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TABLE 14-21 Properties of Stainless Steel (*Continued*)

Material type	310	316	316L	321	347	405
Structure of material	Austenitic	Austenitic	Austenitic	Austenitic	Austenitic	Ferritic
Hardening properties	Nonhardening	Nonhardening	Nonhardening	Nonhardening	Nonhardening	Hardenable
Tensile strength, lb/in.$^2 \times 10^3$	90	85	75	80–90	95	65–70
Yield strength, lb/in.$^2 \times 10^3$	45	35	30	35	40	40
Elongation, %, 2 in.	40–50	50–60	50–60	55	45–50	25–30
Reduction of area, %	50–60	70	70	65	60–65	60
Modulus of elasticity, in tension, lb/in.$^2 \times 10^6$	20–30	29	29–30	29	28	29
Hardness, Brinell	180 max	200 max	180 max	200 max	185 max	150
Hardness, Rockwell	B90 max	B95 max	B90 max	B95 max	B90 max	B75
Magnetic permeability at 200 H, annealed	1.01	1.02	1.02	1.02	1.02	Magnetic
Electrical resistivity, μΩ, cm at 68°F	78.0	74.0	72.0	72.0	72.0	57.0
Heat resistance, max. °F, intermittent service	1900	1600	1600	1600	1450	1250
Machinability index, %	40–45	45	45	50	50	60
Drawability, stamping	Good	Good	Good	Good	Good	Fair
Weldability	Good	Excellent	Excellent	Excellent	Excellent	Good
Approximate price range, %	83–110	60–80	60–90	60	60–85	40–55
Carbon (C), %	0.25	0.08	0.03	0.08	0.08	0.08
Manganese (Mn), %	2.0	2.0	2.0	2.0	2.0	1.0
Silicon (Si), %	1.5	1.0	1.0	1.0	1.0	1.0
Chromium (Cr), %	24–26	16–18	16–18	17–19	17–19	11.5–14.5
Nickel (Ni), %	19–22	10–14	10–14	9–12	9–13	
Other elements, %		2–3 Mo	2–3 Mo			

(*Continued*)

TABLE 14-21 Properties of Stainless Steel (*Continued*)

Material type	410	416	420	430	440C
Structure of material	Martensitic	Martensitic	Martensitic	Ferritic	Martensitic
Hardening properties	Hardenable	Hardenable	Hardenable	Hardenable	Hardenable
Tensile strength, lb/in.$^2 \times 10^3$	75	75	95	75	110
Yield strength, lb/in.$^2 \times 10^3$	40	40–45	55	45–50	65
Elongation, %, 2 in.	35	30	25	30	14
Reduction of area, %	70	65	55	65	25
Modulus of elasticity, in tension, lb/in.$^2 \times 10^6$	29	29	29	29	30
Hardness, Brinell	200 max	180 max	190 max	200 max	250 max
Hardness, Rockwell	B95 max	B90 max	B95	B95 max	B105 max
Magnetic permeability at 200 H, annealed	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic
Electrical resistivity, μΩ, cm at 68°F	57.0	57.0	55.0	60.0	60.0
Heat resistance, max. °F, intermittent service	1250	1250	N/A	1500	1400
Machinability index, %	60	93	54	55	40
Drawability, stamping	Fair	Fair	Fair	Fair	Fair
Weldability	Fair	Limited	N/A	Fair	Limited
Approximate price range, %	40–45	40	45	40	51
Carbon (C), %	0.15	0.15	0.15 min	0.12	0.95–1.2
Manganese (Mn), %	1.0	1.25	1.0	1.0	1.0
Silicon (Si), %	1.0	1.0	1.0	1.0 max	1.0
Chromium (Cr), %	11–14	12–14	12–14	16–18	16–18
Nickel (Ni), %	0.5	0.5		0.5 max	
Other elements, %					0.75 Mo

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Temper designation follows the basic coded description, separated by a dash, as 6061-T4. The additional coded information may be explained as follows:

-F	As fabricated
-0	Annealed and recrystallized, wrought materials only
-H	Strain-hardened, without heat treatment, wrought materials only. This designation is always followed by a number, indicating the particular strain-hardening process.
-H1	Strain-hardened only
-H2	Strain-hardened and partially annealed
-H3	Strain-hardened and stabilized
-T	Thermally treated material, obtaining other than previously described qualities. This designation is always followed by another digit as shown:
-T1	Partially solution heat-treated and naturally aged
-T2	Annealed, cast materials only
-T3	Solution heat-treated and cold-worked
-T4	Solution heat-treated and naturally aged
-T5	Artificially aged
-T6	Solution heat-treated and artificially aged
-T7	Solution heat-treated and stabilized
-T8	Solution heat-treated, cold-worked, and afterward artificially aged
-T9	Solution heat-treated, artificially aged, and afterward cold-worked
-T10	Artificially aged and afterward cold-worked
-T42	Solution heat-treated to attain different mechanical properties from those of -T4 temper
-T62	Solution heat-treated, artificially aged, to obtain different mechanical properties from those of -T6 temper
-TX52	Stress relieved by compressing
-TX53	Stress relieved by thermal treatment
-W	Solution heat-treated

The final amount of strain hardening is indicated by a number following the designation -H1, -H2, -H3, as:

H111	Strain-hardened less than the controlled H11 temper
H112	Temper acquired from shaping processes without being particularly controlled
H311	Strain-hardened less than the controlled H31 temper

14-5-3-1 Types of Aluminum Alloys. Aluminum alloys, as grouped into the above series, display various properties particular to their designation.

1000 series aluminium alloys are almost pure aluminum, with mechanical properties at the low level but with a high workability, ductility, corrosion resistance, chemical and weathering effect resistance, and conductivity, thermal and electrical. It is frequently used for reflectors, fan blades, dials, nameplates, and ductwork.

2000 series aluminum alloys are stronger than the previous group, with the same ductility but lower corrosion resistance, as it may become affected by intergranular corrosion.

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TABLE 14-22 Mean Values of Materials (at Room Temperature)

Material	Modulus of elasticity, KSI	Shear strength, KSI	Poisson's ratio
Steel	30.5	11.75	0.30
Gray iron	16	6.25	0.25
Copper	17.4	6.37	0.35
Bronze	16	6.1	0.35
Brass	13.75	5	0.35
Aluminum alloys	10.16	3.9	0.33
Magnesium alloys	4.9	2	0.30
Zinc, drawn	12	4.79	0.27
Lead	2.5	0.87	0.45
Glass	8.7	3.48	0.23

Sheet material is usually coated with a high-purity alloy, to provide for galvanic protection of the core. The material may be solution heat-treated for optimal properties. In its 2024 form, this alloy is used mainly for aircraft applications.

3000 series aluminum alloys; in this series, 3003 is the most popular grade. It displays good ductility, which designates it for drawing applications, and is widely used in the manufacture of chemical equipment, kitchenware, truck and van panels, shelves, and refrigerator liners.

4000 series aluminum alloys can have their melting point lowered without subsequent brittleness of the material. For these properties such materials are used as welding rods, brazing rings, and similar applications. Most of 4000 series alloys cannot be heat-treated.

5000 series aluminum alloys are widely utilized for automotive parts, such as body trims, as well as gas tanks. Applications further include aircraft parts, pressure vessels, marine products, welded constructions, refrigerator components, etc. This type of material offers good welding characteristics, along with a resistance to corrosion even in marine applications. Alloys with greater than 3.5 percent of magnesium content should not be exposed to either increased amounts of cold work or heat. Higher operating temperatures, such as those exceeding 150°F, may bring about a risk of stress-corrosion appearance within these materials.

6000 series aluminum alloys are heat-treatable and combine good formability, along with good corrosion resistance. Their strength is somewhat lower than that of 2000 series alloys. The most often used alloy of this group of materials is 6061, which is valued for its versatility. This material is utilized for manufacture of tubes, pipes, tanks, furniture, chemical equipment, sailboats, fittings, couplings, apparatus components, etc.

7000 series aluminum alloys display considerable strength, for which reason these materials are often used for manufacture of highly stressed parts. Materials of this group may be heat-treated. Their additional uses are within aircraft parts manufacturing as a material for keys, and where higher strengths than those exhibited by 2024 alloy are needed. Tables 14-22 through 14-24 show various properties and characteristics of aluminum alloys.

14-5-4 Nickel and Nickel Alloys

Nickel is known for its high heat resistance, corrosion resistance, and electricity-conductive properties. The usage of this material includes various chemical and electrical-related applications, with heavy involvement within the food and drug industry. Table 14-25 lists mechanical properties of nickel.

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TABLE 14-23 Properties of Selected Aluminum Alloys

Material type	Tensile strength, KSI	Yield strength, KSI	Shear strength, KSI	Modulus of elasticity, KSI	Elongation, % in 2 in.		Endurance limit, KSI	Hardness, Brinell, 500 kg, ϕ10 mm
					1/16 in. thick	1/2 in. thick		
1100-0	13	5	9–9.5	10.0	35	45	5	23
1100-H12	15.5–16	14–15	10	10.0	12	25	6	28
1100-H14	17.5–18	16–17	11	10.0	9	20	7	32
1100-H16	20–21	18–20	12	10.0	6	17	8.5–9	38
1100-H18	24	22	13	10.0	5	15	8.5–9	44
2011-T3	55	43	32	10.2		15	18	95
2011-T6	57	39	34	10.2		17	18	97
2011-T8	59	45	35	10.2		12	18	100
2014-0	27	14	18	10.6		18	13	45
2014-T4	62	40–42	38	10.6		20	20	105
2014-T6	70	60	42	10.6		13	18	135
2017-0	26	10	18	10.5		22	13	45
2017-T4	62	40	38	10.5		22	18	105
2018-T61	61	46	39	10.8		12	17	120
2024-0	17	11	18	10.6	19–20	22	13	47
2024-T3	70	50	41	10.6	18		20	120
2025-T6	58	37	35	10.4		19	18	110
2219-0	25	10		10.6	20			
2219-T31	52–54	36.5	33	10.6	17			
3003-0	16	6	11	10.0	30	40	7	28
3003-H12	19	18	12	10.0	10	20	8	35
3003-H14	22	21	14	10.0	8	16	9	40
3003-H16	26	25	15	10.0	5	14	10	47
3003-H18	29	27	16	10.0	4	10	10	55
3004-0	26	10	16	10.0	20	25	14	45
3004-H32	31	25	17	10.0	10	17	15	52
3004-H34	35	29	18	10.0	9	12	15	63
3004-H36	38	32	20	10.0	5	9	15.5	70
3004-H38	41	35	21	10.0	5	6	16	77

(*Continued*)

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TABLE 14-23 Properties of Selected Aluminum Alloys (*Continued*)

Material type	Tensile strength, KSI	Yield strength, KSI	Shear strength, KSI	Modulus of elasticity, KSI	Elongation, % in 2 in.		Endurance limit, KSI	Hardness, Brinell, 500 kg, ϕ10 mm
					1/16 in. thick	1/2 in. thick		
3105-0	17	8	12	10.0	24			
3105-H12	22	19	14	10.0	7			
3105-H14	25	22	15	10.0	5			
3105-H16	28	25	16	10.0	4			
4032-T6	55	46	38	11.4		9	16	120
5005-0	18	6	11	10.0	30			28
5005-H12	20	19	14	10.0	10			
5005-H14	23	22	14	10.0	6			
5005-H16	26	25	15	10.0	5			
5005-H18	29	28	16	10.0	4			
5005-H32	20	17	14	10.0	11			36
5005-H34	23	20	14	10.0	8			41
5005-H36	26	24	15	10.0	6			46
5050-0	21	8	14.5	10.0	24		12	36
5050-H32	25	21	16.5	10.0	9		13	46
5050-H34	28	24	17.5	10.0	8		13	53
5050-H36	30	26	18.5	10.0	7		14	58
5052-0	27.5	12.5	18	10.2	25	30	16	47
5052-H32	33.5	27.5	20	10.2	12	18	17	60
5052-H34	37.5	31	21	10.2	10	15	18	67.5
5052-H36	39.5	34.5	23	10.2	8	10	19	73.5
5056-0	42	22	26	10.3		35	20	65
5056-H18	63	59	34	10.3		10	22	105
5086-0	38	17	23	10.3	22	30		
5086-H32	42	30	25	10.3	12			
5086-H34	47	37	27.5	10.3	10	14		
5154-0	35	17	22	10.2	27	30	17	58
5154-H32	39	30	22.5	10.2	15	18	18	67
5154-H34	42	33	24	10.2	13	16	19	73

5154-H36	45	36	26	10.2	12	14	20	78
5252-H25	34	25	21	10.0	11			68
5252-H38	41	35	23	10.0	5			75
5254-0	35	17	22	10.2	27	30	17	58
5254-H32	39	30	22.5	10.2	15		18	67
5254-H34	42	33	24	10.2	13		19	73
5254-H36	45	36	26	10.2	12	14	20	78
5357-0	19	7	12	10.2	25			
5357-H25	27	23	16	10.2	10			
5456-0	45	23	27	10.3	24	20		
5456-H24	54	41	31	10.3	12			
5557-0	16	6	10	10.2	25			
5557-H25	25	21	15	10.2	10			
5652-0	28	13	18	10.2	25	30	16	47
5652-H32	33	28	20	10.2	12	18	17	60
5652-H34	38	31	21	10.2	10	14	18	68
5652-H36	40	35	23	10.2	8	10	19	73
6061-0	18	8	12	10.0	25	30	9	30
6061-T4	35	21	24	10.0	22	25	14	65
6061-T6	45	40	30	10.0	12	17	14	95
6062-0	17.5	7–8	12	10.0		30	8.5	28
6062-T4	35	21	24	10.0		25	13.5	65
6062-T6	45	40	30	10.0		17	13.5	95
6063-0	13	7	10	10.0			8	25
6063-T1	22	13	14	10.0	20		9	42
6063-T4	25	13	16	10.0	22			
6063-T5	27	21	17	10.0	12		10	60
6063-T6	35	31	22	10.0	12	18	10	73
7001-0	37	22		10.3		14		60
7001-T6	98	91		10.3		9	22	160
7075-0	33	15	22	10.4	17	16		60
7075-T6	82.5	72.5	48.5	10.4	11	11	23.5	150
7187-0	33	15	22	10.4	15	16		
7178-T6	88	78	52	10.4	10	11		

Note: Values presented in this table are to be considered average, with no variation owing to shape and size of parts or the method of their production taken into account.

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TABLE 14-24 Aluminum—Working Characteristics

Type	Condition	Corrosion resistance	Cold-working suitability	Machinability
1100-0	Annealed	5	5	4
1100-H18	Hard	5	4	4
3003-0	Annealed	5	5	4
3003-H18	Hard	5	3	4
3004-0	Annealed	5	5	4
3004-H38	Hard	5	3	4
2011-T3	Heat-treated	2	3	5
2014-T4	Heat-treated	3	3	5
2014-T6	Heat-treated and aged	3	3	5
2017-T4	Heat-treated	3	4	5
2024-T3	Heat-treated	3	3	5
5050-0	Annealed	5	5	4
5050-H38	Hard	5	3	4
5052-0	Annealed	5	5	4
5052-H38	Hard	5	3	4
6053-T4	Heat-treated	5	4	4
6053-T6	Heat-treated and aged	5	3	4
5056-0	Annealed	5	5	4
5056-H38	Hard	4	4	4
5154-0	Annealed	5	4	3
5154-H34	Hard	5	4	3
5154-H38	Hard	5	4	3
6061-T4	Heat-treated	5	4	4
6061-T6	Heat-treated and aged	5	4	4
7075-T6	Heat-treated and aged	3	2	5

Relative evaluation, where 1 is the lowest rating and 5 is the greatest.

14-5-5 Copper Alloys

Copper is usually alloyed with other ingredients such as silicon or beryllium and cobalt. Copper-silicon alloys are materials of high strength, resistant to corrosion, with free machining qualities.

TABLE 14-25 Mechanical Properties of Nickel

Material type	Material condition	Tensile strength, KSI	Yield strength, 0.2% offset, KSI	Elongation, % in 2 in.	Modulus of elasticity, KSI	Hardness, Rockwell
Monel, 400	Annealed strip	70	25–30	35	26	68B
Monel, K-500	Annealed strip	90	40	20	26	75B
Monel, R405	Annealed rods	75	35	35		
Inconel, 600	Annealed strip	80	30	30	31	84B
Inconel, 800	Annealed strip	75	30	30	31	84B max
Nickel, 200	Annealed strip	55	15		30	64B
Duranickel, 301	Annealed strip	90	35		30	90B

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TABLE 14-26 Physical Properties of Copper Alloys

Material type	Material condition	Tensile strength, KSI	Yield strength, KSI	Elongation, % in 2 in.	Hardness, Rockwell
Copper, 110	Annealed sheet	33	10	35	F35
Bronze, 210	Annealed sheet	35	11	38	F45
Bronze, 220	Annealed sheet	37	12	40	F45
Brass, yellow, 268	Annealed sheet	45	17	60	B15
Brass, yellow, 274	Annealed sheet	54	20	45	B45
Aluminum bronze	Annealed sheet	55	22	65	B35
Everdur	Annealed sheet	58	22	60	B35
Cupronickel, 30%	Annealed sheet	55	22	40	B35
Nickel-silver, 10%	Annealed sheet	55	20	42	B30
Nickel-silver, 18%	Annealed sheet	60	22	45	B45
Phosphor bronze, 50	Annealed sheet	40	14	48	F60
Phosphor bronze, 51	Annealed sheet	48	20	50	B28
Phosphor bronze, 52	Annealed sheet	60	24	65	B50

Beryllium copper alloys may be separated into two basic groups: those with beryllium content exceeding 1 percent, which are alloys of a considerable hardness and strength, and those with a beryllium content of less than 1 percent, which are valued for good thermal and electrical qualities, such as good conductivity and nonmagnetism. Physical properties are given in Table 14-26.

14-6 COMPARISON OF MATERIALS WORLDWIDE

A comparison of designations for various material types worldwide is included in Table 14-27. It contains the material denominations used in England, Germany, France, Italy, Japan, Sweden, and the Czech Republic. Properties and composition of materials are not described, the list being limited to their equivalent names or codes within that particular nation's system.

14-7 HEAT TREATMENT

One of the most important factors to be considered when evaluating the possibility of heat treatment for any particular material is the effect it may exert on the size of its grain. Since all fine-grained structures display much better toughness and less inclination to warpage at higher attained hardnesses, such materials are definitely preferable for this procedure.

The greatest danger of the emergence of grain-related irregularities may be encountered at temperatures above the critical range, in parts previously cold-worked, when an effect known as grain growth may occur. This condition was discussed in Sec. 9-11-4, "Grain Growth."

Suitability of Materials for Heat Treatment. The suitability of materials for heat treatment is given by the ease of the hardening process or by the depth of hardness penetration achievable within that material. Such suitability, otherwise called hardenability of the material, is

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TABLE 14-27 Worldwide Steel and Alloy Comparison Chart

U.S. AISI-ASTM	Germany No.	Germany DIN	Belgium, NBN	France, AFNOR	Great Britain, B.S.
1010	1.0301	C10		AF34C10	045M10, 040A10
	1.1121	Ck10	C10-2	XC10	1449 10CS
1015	1.0401	C15		AF37C12, XC18	040A15, 080M15
	1.1141	Ck15	C16-2	XC15	1449 17CS
1020	1.0402	C22	C25-1	AF42C20, XC25	050A20, 055M15
1020, 1023	1.1151	Ck22	C25-2	XC25, XC18	050A20 (055M15)
1022	1.1133	20Mn5		20M5	120M19
1023, 1020	1.1151	Ck22	C25-2	XC25, XC18	050A20 (055M15)
1025	1.0406	C25	C25-1	AF50C30	070M26
	1.1158	Ck25	C25-2	XC25	
1035	1.0501	C35	C35-1	AF55C35, XC38	060A35, 080M36
	1.1180	Cm35	C35-2	XC32	1449 40CS
	1.1181	Ck35	C35-3	XC38H1, XC32	
	1.1183	Cf35	C36	XC38H1TS	060A35
1039	1.1157	40Mn4		35M5	150M36
1040	1.0511	C40	C40-1	AF60C40	060A40
	1.1186	Ck40	C40-2	XC42H1	080A40, 080M40
1045	1.0503	C45	C45-1	AF65C45	080M46
	1.1191	Cf45	C45-2	XC42H1, XC45	080M46, 060A47
	1.1193	Ck45	C45-3	XC48	
	1.1201	Cm45	C46	XC42H1TS	
1050	1.1206	Cf53	C53	XC48H1	060A52, 070M55
	1.1213	Ck50		XC48H1TS	080M50
1055	1.0535	C55	C55-1		070M55
	1.1203	Ck55	C55-2	XC55H1	070M55, 060A57
	1.1209	Cm55	C55-3	XC55H1	070M55
1060	1.0601	C60	C60-1	AF70C55	080A62
	1.1221	Ck60	C60-2	XC60	080A62, 060A62
1070	1.1231	Ck67		XC68	060A67
1078, 1080	1.1248	Ck75		XC75	060A78
1086	1.1269	Ck85		XC90	
1095	1.1274	Ck101		XC100	060A96
1108	1.0721	10S20		10F1	(210M15)
1139	1651-70	35S20		38C4	212M36
1140	1.0726	35S20		35MF6	212M36
1146	1.0727	45S20		45MF4	212M44
1212	1.0711	9S20			220M07
1213	1.0715	9SMn28		S250	230M07
1215	1.0736	9SMn36		S300	240M07
	1.1165	30Mn5	28Mn6	20M5	120M36, 150M28
	1.1170	28Mn6		35M5	
1335	1.1167	36Mn5		40M5, 35M5	150M36
1518	1.1133	20Mn5		20M5	120M19
1536	1.1166	34Mn5			
2515	1.5680	12Ni19	12Ni20	Z18N5	
3115	1.5713	13NiCr6		10NC6	
3135	1.5710	36NiCr6		35NC6	640A35
3140	1.5711	40NiCr6			640M40
3310, 3415	1.5752	14NiCr14	13NiCr12	12NC15	655M13, 655A12
3415	1.5752	14NiCr14	13NiCr12	12NC15	655M13, 655A12
3415, 3310	1.5732	14NiCr10		14NC11	
3435	1.5736	36NiCr10		30NC11	
4130	1.7218	25CrMo4	25CrMo4	25CD4	1717CDS110
4135	1.2330	35CrMo4		34CD4	708A37

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Italy, UNI	Japan, JIS	Sweden, SS	Czech, CSN	Spain, UNE
C10	S10C			F.151, F.151.A
	S10C, S9CK	1265	12 010	F.1510-C10k
C15, C16		1350	12 023	F.111, F1110-C15k
	S15C, S15CK	1370		F.1511-C16k
C20, C21		1450	11 353, 12 021	F.112
C20, C25	S20C, S20CK, S22C			F.1120-C25k
C22Mn3	SMnC420			F.1515-20Mn6
C20, C25	S20C, S20CK, S22C			F.1120-C25k
C25	S25C		12 024	F.1120-C25k
C35		1550	11 453	F.113
		1572	12 040	F.1135-C35k-1
C35	S35C			F.1130-C35k
C36, C38	S35C			
C40	S40C		12 041	F.114A
C42, C43, C45	S45C, S50C	1650	12 050	F.114
C46		1660		F.1140-C45k
		1672		F.1145-C45k-1
	S50C	1674	12 051	
C55		1655	12 060	
C55	S55C			F.1150-C55k
				F.1155-C55k-1
C60			12 061	
C60	S58C	1665, 1678		
C70		1770	13 180	
C75		1774, 1778		
C90				
C100	SUP4	1870		
CF10S20			11 110	F.2121-10S20
		195703	11 140	
		1957		F.210.G
		1973		
CF9S22	SUM21			
CF9SMn28	SUM22	1912	11 109	F.2111-11SMn28
CF9SMn36				F.2113-12SMn35
C28Mn	SMn433H, SCMn2		13 141	F.8211-30Mn5
	SCMn1			F.8311-AM30Mn5
	SMn438 (H), SCMn3	2120		F.1203-36Mn6
				F.8212-36Mn5
G22Mn3	SMnC420			F.1515-20Mn6
	SMn433			TO.B
			16 520	
16CrNi4			16 220	
SNC236			12 042, 16 240	
	SNC815(H)			
	SNC815(H)			
16NiCr11	SNC415(H)			
35NiCr9	SNC631(H)			
25CrMo4(KB)	SCM420, SCM430	2225	15 130, 15 131	F.8372-AM26CrMo4
				F.8330-AM25CrMo4
				F.1256-30CrMo4-1
35CrMo4		2234	15 141	F.8331-AM34CrMo4

(*Continued*)

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TABLE 14-27 Worldwide Steel and Alloy Comparison Chart (*Continued*)

U.S. AISI-ASTM	Germany No.	Germany DIN	Belgium, NBN	France, AFNOR	Great Britain, B.S.
4135, 4137	1.7220	34CrMo4	34CrMo4	35CD4	708A37
4137	1.7225	42CrMo4		38CD4	708A37
4140	1.7225	42CrMo4	42CrMo4	42CD4	708M40
4140, 4142	1.7223	41CrMo4	41CrMo4	42CD4 TS	708M40
4142	1.2332	42CrMo4	42CrMo4	42CD4	
	1.7225	47CrMo4			
4142, 4140	1.7223	41CrMo4	41CrMo4	42CD4 TS	708M40
4145	1.7228	50CrMo4			708H45
4147					708A47
4150	1.7228	50CrMo4			708A47
4340	1.6562	34CrNiMo6	35CrNiMo6	35NCD6	311-Type 6
	1.6565	40NiCrMo6			817M40
	1.6582	40NiCrMo73			
4419	1.5419	22Mo4			
4520	1.5423	16Mo5	16Mo5		1503-245-420
5015	1.7015	15Cr3	15Cr2	12C3	523M15
5045, 5046	1.7006	46Cr2	46Cr2	42C2	
5115	1.7131	16MnCr5	16MnCr5	16MC5	527M17
5120	1.7147	20MnCr5		20MC5	
5130	1.7030	28Cr4			
	1.7033	34Cr4		32C4	530A30
5132	1.7037	34CrS4	34Cr4	32C4	530A32
5135	1.7034	37Cr4	37Cr4	38C4	530H36
5140	1.7035	41Cr4	41Cr4	42C4	530M40, 530A40
	1.7045	42Cr4		42C4 TS	530A40
5155	1.7176	55Cr3	55Cr3	55C3	527A60
6150	1.8159	50CrV4	50CrV4	50CV4	735A50
8620	1.6523	21NiCrMo2		20NCD2	805M20
8720	1.6543	21NiCrMo22			805A20
8740	1.6546	40NiCrMo22	40NiCrMo2	40NCD2	311-Type 7
9255	1.0903	51Si7	50Si7	51S7	250A53
	1.0904	55Si7	55Si7	55S7	
9260	1.0909	60Si7	60Si7	60S7	250A58
9262	1.0961	60SiCr7	60SiCr8	60SC7	250A61
9314	1.5752	14NiCr14	13NiCr12	12NC15	655M13, 655A12
9840	1.6511	36CrNiMo4		40NCD3	816M40
301	1.4310	X12CrNi177		Z12CN17.07	301S21
				Z12CN18.07	
303	1.4305	X10CrNiS189		Z10CNF18.09	303S21
304, 304H	1.4301	X5CrNi1810		Z6CN18.09	304S15, 304S16
					304S31
308, 305	1.4303	X5CrNi1812		Z8CN18.12	305S19
304L	1.4306	X2CrNi1911		Z2CN18.09	
		G-X2CrNi189		Z2CN18.10	
				Z3CN19.10M	
304LN	1.4311	X2CrNiN1810		Z2CN18.10Az	304S62
308, 305	1.4303	X5CrNi1812		Z8CN18.12	305S19
309	1.4828	X15CrNiSi2012		Z15CNS20.12	(309S24)
309S	1.4833	X7CrNi2314		Z15CN24.13	309S24

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Italy, UNI	Japan, JIS	Sweden, SS	Czech, CSN	Spain, UNE
35CrMo4	SCM432, SCCrM3	2234		F.8231-34CrMo4
	SCM435H			F.1250-35CrMo4
42CrMo4	SCM440		15 142	
42CrMo4	SCM440 (H)	2244	15 142	F.8332-AM42CrMo4
				F.8232-42CrMo4
				F1252-40CrMo4
41CrMo4	SCM440	2244		
40CrMo4	SCM440(H)	2244		F.8232-42CrMo4
42CrMo4				F.8332-AM42CrMo4
41CrMo4	SCM440	2244		F.1252-40CrMo4
	SCM445			
	SCM445			
	SCM445 (H)		15 261	
35NiCrMo6 KB				
		2541	16 243	F.1272-40NiCrMo7
40NiCrMo7(KB)	SNCM439		16 341	
	SNCM447		16 342	
G22Mo5	SCPH11			
16Mo5				F.2602-16Mo5
	SCr415(H)		14 120	
45Cr2		2511		
16MnCr5				F.1516-16MnCr5
				F.1517
20MnCr5	SMnC420H			F.150D
			15 231	
	SCr435		14 141	
34Cr4(KB)	SCr430(H) SCr435H		14 141	F.8221-35Cr4
36CrMn4, 38Cr4	SCr435H		14 140	F.1201-38Cr4
41Cr4	SCr440	2245	14 140	F.1202-42Cr4
	SCr440(H)			
55Cr3	SUP9 (A)	2253		F.1431-55Cr3
50CrV4	SUP 10	2230	15 260	F.1430-51CrV4
20NiCrMo2	SNCM220(H)	2506	16 125, 15 124	F.1522-20NiCrMo2
				F.1534-20NiCrMo31
				F.1524-20NiCrMo3
40NiCrMo2(KB)	SNCM240		13 261	F.1204-40NiCrMo2
48Si7, 50Si7		2085, 2090		F.1440-56Si7
55Si8				F.1450-50Si7
			13 270	F.1441-60Si7
60SiCr8	SUP7			F.1442-60SiCr8
	SNC815(H)			
38NiCrMo4(KB)			16 243	F.1280-35NiCrMo4
X12CrNi1707	SUS301		17 241, 17 242	F.3517-X12CrNi1707
X10CrNiS1809	SUS303	2346	17 243	F.3508-X10CrNiS18-09
X5CrNi1810	SUS304	2332, 2333		F.3504-X6CrNi1910
				F.3541-X5CrNi18-10
				F.3551-X5CrNi1811
X8CrNi1910	SUS305			F.3513-X8CrNi18-12
X2CrNi1811	SCS19, SUS304L	2352, 2333		F.3505-X2CrNi19-10
GX2CrNi1910				
X2CrNiN1811	SUS304LN	2371		
X8CrNi1910	SUS305			F.3513-X8CrNi18-12
	SUH309		17 251	F.3312-X15CrNiSi20-12
X6CrNi2314	SUS309S			

(*Continued*)

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TABLE 14-27 Worldwide Steel and Alloy Comparison Chart (*Continued*)

U.S. AISI-ASTM	Germany No.	Germany DIN	Belgium, NBN	France, AFNOR	Great Britain, B.S.
310, 314	1.4841	X15CrNiSi2520		Z12CNS25.20 Z15CNS25.20	
310S	1.4845	X12CrNi2521		Z12CN25.20	310S24
314, 310	1.4841	X15CrNiSi2520		Z12CNS25.20 Z15CNS25.20	
316	1.4401	X5CrNiMo17122		Z6CND17.11	316S16, 316S31
	1.4436	X5CrNiMo17133		Z6CND17.12	
316L	1.4404	X2CrNiMo17132		Z2CND17.12	316S11, 316S12
	1.4435	X2CrNiMo18143		Z2CND17.13	
		G-X2CrNiMo1810		Z2CND18.13 Z3CND19.10M	
316LN	1.4406	X2CrNiMoN17122		Z2CND17.12Az	316S61
	1.4429	X2CrNiMoN17133		Z2CND17.13Az	316S62
316Ti	1.4571	X6CrNiMoTi17122		Z6CNDT17.12	320S17, 320S31
	1.4573	X10CrNiMoTi1812			320S33
317	1.4449	X5CrNiMo1713			317S16
317L	1.4438	X2CrNiMo18164		Z2CND19.15	317S12
318	1.4583	X10CrNiMoNb1812			
321	1.4541	X6CrNiTi1810		Z6CNT18.10	321S12, 321S20
	1.4878	X12CrNiTi189		Z6CNT18.12(B)	321S31
329	1.4460	X8CrNiMo275			
330	1.4864	X12NiCrSi3616		Z12NCS35.16 Z12NC37.18 Z12NCS37.18	NA17
347	1.4550	X6CrNiNb1810		Z6CNNb18.10	347S17, 347S31
348	1.4546	X5CrNiNb1810			347S17, 347S18
403, 410S	1.4001	X7Cr14		Z3C14	
405	1.4002	X6CrAl13		Z6CA13	405S17
409	1.4512	X5CrTi12		Z6CT12	409S19
410	1.4006(G-)	X10Cr13		Z12C13	410S21, 410C21
410S, 403	1.4000	X6Cr13		Z6C13	403S17
416	1.4005	X12CrS13		Z12CF13	416S21
420	1.4021	X20Cr13		Z20C13	420S37
430	1.4016	X6Cr17		Z8C17	430S15
	1.4742	X10CrAl18		Z10CAS18	
430Ti, XM8	1.4510	X6CrTi17		Z8CT17	
431	1.4057	X20CrNi17 2		Z15CN16.02	431S29
433	1.4113	X6CrMo17		Z8CD17.01	434S17
446	1.4762	X10CrAl24		Z10CAS24	
430F	1.4104	X12CrMoS17		Z10CF17	
440C	1.4125	X105CrMo17		Z100CD17	
A2	1.2363	X100CrMoV51		Z100CDV5	BA2
D2	1.2379	X155CrVMo121		Z160CDV12	BD2
D3	1.2080	X210Cr12		Z200 C12	BD3
L2	1.2210	115CrV3			
L3	1.2067	100Cr6		Y100 C6	BL3
L6	1.2713	55NiCrMoV6		55NCDV7	
M2	1.3343	S6-5-2		Z85WDCV 06--05-04-02	BM2
M3	1.3342	SC6-5-2		Z90WDCV 06--05-04-02	
M7	1.3348	S2-9-2		Z100DCWV 09-04-02-02	
XM8, 430Ti	1.4510	X6CrTi17		Z8CT17	
M33	1.3249	S2-9-2-8			BM34

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Italy, UNI	Japan, JIS	Sweden, SS	Czech, CSN	Spain, UNE
X16CrNiSi2520	SUH310			F.3310-X15CrNiSi25-20
(X6CrNi2520)	SUH310, SUS310S	2361		F.331
X16CrNiSi2520	SUH310			F.3310-X15CrNiSi25-20
X5CrNiMo1712	SUS316	2343	17 352	F.3534-X6CrNiMo17-12-03
X5CrNiMo1713		2347		F.3543-X5CrNiMo17-12
X2CrNiMo1712	SUS316	2348		F.3533-X2CrNiMo17-12-03
X2CrNiMo1713	SUS316L	2353		
GX2CrNiMo1911				
	SUS316L	2348		
X2CrNiMoN1712	SUS316LN	2375		
X2CrNiMoN1713				
X6CrNiMoTi1712		2350		F.3535-X6CrNiMoTi17-12-03
X6CrNiMoTi1713				
(X5CrNiMo1815)	SUS317			
X2CrNiMo18.15	SUS317L	2367		
X6CrNiMoNb1713				
X6CrNiTi1811	SUS321	2337	17 246, 17 247	F.3523-X6CrNiTi1811
			17 248	F.3553-X7CrNiTi18-11
	SUS329 J1	2324		F.3309-X8CrNiMo27-05
	SCH11, SCS11			
	SUH330			F.3313-X12CrNiSi36-16
X6CrNiNb1811	SUS347	2338	17 245	F.3524-X6CrNiNb18-11
				F.3552-X7CrNiNb18-11
X6CrNiNb1811				
	SUS410S			F.8401-AM-X12Cr13
X6CrAl13	SUS405	2302	17 125	F.3111-X6CrAl13
X6CrTi12	SUH409			
X12Cr13, X10Cr13	SUS410	2302	17 021	F.3401-X12Cr13
X6Cr13	SUS403	2301		F.3110-X6Cr13
X12CrS13	SUS414	2380		F.3411-X12CrS13
X20Cr13	SUS420 J1	2303	17 024, 17 029	F.3402-X20Cr13
X18Cr17	SUH21, SUS430	2320	17 041	F.3113-X8Cr17
				F.3153-X10CrAl18
X6CrTi17	SUS430LX			F.3114-X8CrTi17
X16CrNi16	SUS431	2321	17 145	F.3427-X15CrNi16
X8CrMo17	SUS434	2325		
X16Cr26				F.3154-X10CrAl24
X10CrS17	SUS430F	2383		F.3117-X10CrS17
	SUS440C			
X100CrMoV51 KU	SKD12	2260		F.5227, X100CrMoV5
X155CrVMo121KU				
X205Cr12 KU	SKD1		19 436, 19 437	F.5212, X210Cr12
107CrV3 KU			19 423	
				F.5230, 100Cr6
	SKT4			
HS 6-5-2	SKH51	2722	19 829, 19 830	F.5603, 6-5-2
HSC 6-5-3				
HS 2-9-2		2782		F.5607, 2-9-2
X6CrTi17	SUS430LX			F.3114-X8CrTi17
				F.5611, 2-9-2-8

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TABLE 14-27 Worldwide Steel and Alloy Comparison Chart (*Continued*)

U.S. AISI-ASTM	Germany No.	Germany DIN	Belgium, NBN	France, AFNOR	Great Britain, B.S.
M34	1.3249	S2-9-2-8			BM34
M41	1.3246	S7-4-2-5		Z110WKCDV 07-05-04-04-02	
M42	1.3247	S2-10-1-8		Z110DKCWV 09-08-04-02-01	BM42
O1	1.2510	100MnCrW4			BO1
O2	1.2842	90MnCrV8		90MV8	BO2
S1	1.2542	45WCrV7			BS1
T1	1.3355	S18-0-1		Z80WCV18-04-01	BT1
T4	1.3255	S18-1-2-5		Z80WKCV 18-05-04-01	BT4
T5	1.3265	S18-1-2-10			BT5
T15	1.3202	S12-1-4-5			BT15
W1	1.1625 1.1750	C75W, C80W2			BW1A, BW1B
W108	1.1525	C80W1		Y1 90, Y1 80	
W110	1.1545	C105W1		Y1 105	
W112	1.1663	C125W		Y2 120	
W210	1.2833	100V1		Y1 105V	BW2

closely tied to the carbon content of the particular stock: With greater carbon content the hardenability is improved. Low-carbon steels sometimes must first be saturated with carbon elements, or carburized, in order to attain the necessary hardness range.

Hardenability is further affected by the cooling rate of steel, or the speed at which the material must be cooled in order to harden. The depth of hardness penetration with regard to the length of exposure to hardening influences is often assessed as an indicator of hardenability. The depth is always more pronounced in materials with higher carbon content, where the difference between the hardened case and softer core is more apparent. According to Grossmann, a part is heat-treated when its core contains less than 50 percent of martensite.

Some applications rely on low hardenability of steel, however. These are instances where the material is subjected to welding and other temperature-dependent treatments.

Hardenability of a material may be evaluated by heating and quenching a round bar, which is then cut across and the depth of its hardness with reference to the outer circumferential surface is measured on the cross section.

The Jominy test of hardenability uses a testing bar heated to a specified temperature and held there for 30 min. The bar must be previously normalized and free of decarburization, the removal of which may be achieved through machining away the upper surface. One end of the heated bar, as held in a vertical position, is then quenched in water. Its hardness is measured along the length, distancing the measurements in 0.062-in intervals off the quenched end, and the differences of these values are evaluated.

Heat-Treating Process. Heat-treating furnaces can be heated by gas, oil, or electricity. Their atmosphere may be either composed of air, or controlled, in which case it is selectively affected by residues of various burning gases or by removal of carbon dioxide or by devaporizing of the furnace area. In salt bath furnaces, parts are heated by means of electrodes surrounding the salt bath. Their location and design produce an electromagnetic influence within the bath, which by stirring the content aids the distribution of temperature. Salt baths, however, may cause a decarburization of parts if the solution content is not properly controlled.

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				F.5611, 2-9-2-8
HS7-4-2-5			19 851	F.5615, 7-4-2-5
HS 2-9-1-8				F.5617, 2-10-1-8
95MnWCr5 KU		2140	19 314	F.5220, 95MnCrW5
90MnVCr8 KU			19 312, 19 313	
45WCrV8 KU		2710		F.5241, 45WCrSi8
HS 18-0-1	SKH2		19 824	F.5520, 18-0-1
HS 18-1-1-5	SKH3		19 855	F.5530, 18-1-1-5
HS 18-0-1-10	SKH4A			F.5540, 18-0-2-10
			19 857	F.5563, 12-1-5-5
	SKC3, SK5, SK6		19 132, 19 133	F.5107, C80
			19 191, 19 192	
C80KU			19 152	
C100KU		1880	19 221, 19 222	
C120KU	SK2		19 255	F.5123, C120
102V2 KU	SKS43		19 356	

Note: Exchangeability of presented material specifications is possible only after a thorough examination of each material's composition and manufacturing methods.

Cooling of heat-treated parts, otherwise called quenching, is achieved through their immersion in liquids or through their exposure to air, gases, or solids. The liquid cooling media may be water, oil, salt bath, soap bath, lead bath, or a brine, consisting of either sodium carbonate or sodium hydroxide or even sulfuric acid.

The differentiation between various quenching media is based on the speed of the cooling process they can provide, even though some additional aspects are attributable to the outcome as well. With quenching in oil, the hardness of the core comes out lower yet the core becomes tougher than that quenched in water. Oil-quenched materials are also less prone to distortion when compared to water-quenched parts. Where water quench may be considered mild for a 5-in-diameter round part, it may certainly be too drastic for a part a quarter of this size. Still smaller parts are best when hardened in air, while thicker products may benefit by oil quenching.

Generally, steels with lower thermal conductivity and greater coefficient of thermal expansion will suffer from small depth of heat-treatment penetration, of coarser grain and greater distortions during the heat-treating process. Another cause contributing to the emergence of inner stresses within the heat-treated material may be found in

- Unequal distribution of the heat
- Uncompleted austenization
- Decarburization of the parts' surface

Naturally, a proper selection of the heat-treating method, its temperature range, and the quenching media is vital for assessment of a successful outcome of this operation.

Another considerable influence is exerted in the form of the shape of heat-treated parts and their size. The inner tension is always greater in the larger parts, where the difference between the temperature of the core and that of the surface may be increased. Sharp edges,

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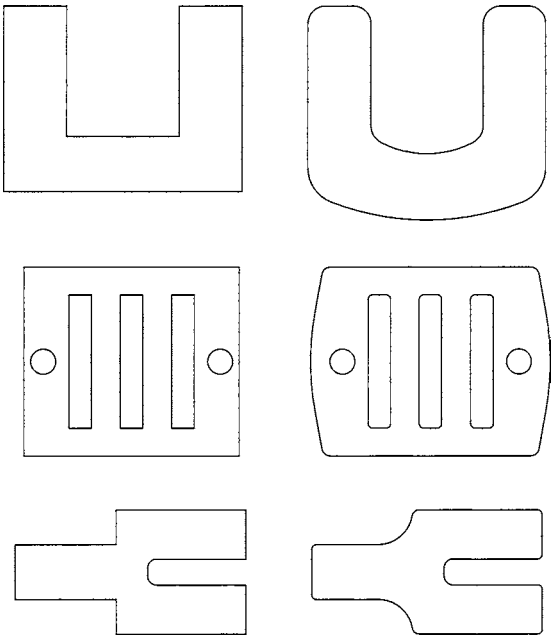

FIGURE 14-13 Shapes of heat-treated parts. Wrong shapes are on left, correct shapes on right.

sharp corners, thin walls, and notches are all detrimental to the results of the heat-treating process (Fig. 14-13). Variations in outcome of the heat-treating process are included in Table 14-28.

Certain areas which need to be protected from the effect of heat treatment are filled with a physical barrier of insulating type for the duration of the process. Such sections are especially the transitions between different thicknesses, or excessively thin walls. Notches and sharp corners may be protected by an encirclement of several strands of wire. Tables 14-29 through 14-32 cover various aspects of hardening, tempering, and heat treatment.

14-7-1 Carburizing

Often heat treatment of metal parts is used to either increase or decrease their hardness, relieve inner stresses, or aid the even distribution of their properties. In the carburizing process, the expected outcome is somewhat different. Here the solid iron-base alloy is heated to a temperature below its melting point and left in the oven to absorb carbon from purposely added carbonaceous materials, be it solids or gases. Carburizing is often followed by quenching, which produces a hardened skin on the part, otherwise called a hardened case.

The reverse of this process is *decarburization*, or loss of carbon content from the material surface, which occurs when it is heated in an environment reacting with its carbon content.

Carburizing is a diffusion process of adding extra carbon particles into the surficial layers of parts. It does not affect the parts' core, as its influence seeps into the body of metal very, very slowly through the surface, affecting only the immediate layers. A thin layer, or a case, becomes austenitized by the increased content of carbon.

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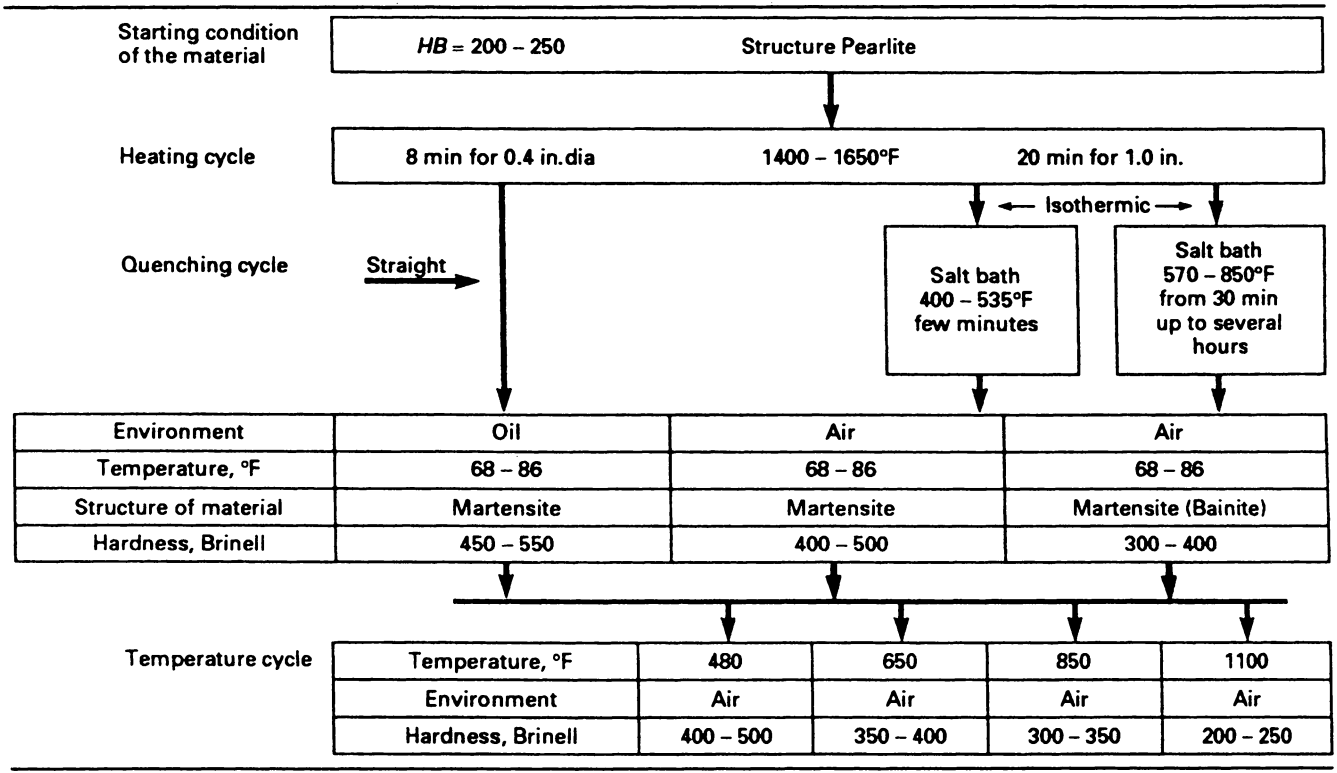
TABLE 14-28 Variation of the Heat-Treatment Process


Starting condition of the material
HB = 200 – 250
Structure Pearlite
Heating cycle
8 min for 0.4 in.dia
1400 – 1650°F
20 min for 1.0 in.
Isothermic
Quenching cycle
Straight
Salt bath 400 – 535°F few minutes
Salt bath 570 – 850°F from 30 min up to several hours
Environment | Oil | Air | Air
Temperature, °F | 68 – 86 | 68 – 86 | 68 – 86
Structure of material | Martensite | Martensite | Martensite (Bainite)
Hardness, Brinell | 450 – 550 | 400 – 500 | 300 – 400
Temperature cycle
Temperature, °F | 480 | 650 | 850 | 1100
Environment | Air | Air | Air | Air
Hardness, Brinell | 400 – 500 | 350 – 400 | 300 – 350 | 200 – 250

SOURCE: Svatopluk Černoch, *Strojně technická příručka*, 1977. Reprinted with permission from SNTL Publishers, Prague, CZ.

TABLE 14-29 Comparison of Properties, Case-Hardening and Hard-Tempering Steels

	Case-hardening steel	Hard-tempering steel
Cost of machining	Lesser	Greater
Cost of forging	Lesser	Greater
Cost of annealing (forgings)	Lesser	Greater
Cost of heat treatment	Greater	Lesser
Distortion due to heat treatment	Greater	Lesser
Straightening difficulties	Lesser	Greater
Hardness of surface	Greater	Lesser
Surface toughness	Lesser	Greater
Wear resistance	Greater	Lesser
Overall strength	Lesser	Greater
Tendency to upset under loading	Greater	Lesser
Tendency to pit under pressure	Lesser	Greater

Initial cost of material is considered equal.

Carbonaceous material utilized for the purpose of carburization can be powdered, liquid, solid, or gas. The latter has the advantage of producing cleaner parts in less time, with more balanced carbon distribution.

Temperatures of the carburizing process are in the vicinity of 1650 to 1700°F for carbon steels. The speed of a process may be increased by raising the temperature, but the austenitic grain will emerge coarser, with too sudden a transition between the core and the surface, the latter being prone to peeling off during the heat treatment.

Heat treatment of carburized parts may be initiated during the carburizing process. The simplest procedure is to continue with the heat-treating cycle right at the termination of the carburizing process. The temperature of the inner core is truly suitable; however, a danger of overheating of the outer surface should be looked into. Since deformations may be the by-product of the method, only simple and straightforward parts should be subjected to such a procedure.

14-7-2 Hardening

The hardening process consists of heating the material to at least some 100°F above the temperature of the transformation point, during which the inner pearlitic structure turns austenitic. Such a temperature is held for a certain amount of time and followed by a rapid cooling, or quenching.

14-7-2-1 Critical Points. The critical or transformation point is also called the *decalescence point.* On reaching such a temperature range, the steel material ceases to increase its own temperature, even though its surroundings are growing hotter. During the cooling sequence, a similar point called the *recalescence point* is encountered. It marks the transformation of austenite back into pearlite. On reaching this temperature range, the steel material, until now continuously releasing its heat and decreasing in temperature, will go through a sudden momentary wave of increased temperature.

These two critical points have considerable importance in the hardening process. If the temperature of the decalescence point is not fully passed, the material will not harden. Subsequently, if the steel is not cooled suddenly before it reaches its recalescence point, no hardening will take place. Usually the recalescence point is anywhere from 85 to 215°F lower than the decalescence point.

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TABLE 14-30 Hardening and Tempering Treatment for Tool and Die Steels*

AISI steel type	Preheat temp., °F	Rate of heating for hardening	Hardening temp., °F	Minimum time at temp., min	Quenching medium	Tempering temp., °F	Depth of hardening	Resistance to decarburization	Maximum tempered hardness, Rockwell C
W1		Slow	1425–1500	15	Brine or water	325–550	Shallow	Best	64
W2		Slow	1425–1500	15	Brine or water	325–550	Shallow	Best	65
O1	1200 or none†	Slow	1450–1500	15	Oil	325–500	Medium	Very good	62
O2	1200 or none†	Slow	1400–1475	15	Oil	325–500	Medium	Very good	62
O6	1200 or none†	Slow	1450–1500	30	Oil	300–600	Medium	Very good	63
A2	1250	Slow	1725–1800	30	Air	350–950	Deep	Fair	62
A4	1250	Slow	1500–1600	20	Air	300–800	Deep	Good	62
A6	1250	Slow	1500–1600	20	Air	300–800	Deep	Good	60
A7	1250	Slow	1700–1800	30	Air	300–1000	Deep	Fair	67
A8	1250	Slow	1800–1850	30	Air	300–950	Deep	Low	60
A10		Slow	1450–1500	30	Air	300–600	Deep	Good	63
D2	1450	Very slow	1800–1850	45	Air	300–950	Deep	Fair	62
D3	1450	Very slow	1750–1825	45	Oil	300–950	Deep	Fair	63
D4	1450	Very slow	1775–1850	45	Air	300–950	Deep	Fair	62
D5	1450	Very slow	1800–1850	45	Air	300–950	Deep	Fair	63
D7	1450	Very slow	1875–2000	45	Air	300–1000	Deep	Fair	67
S1		Slow	1650–1800	20	Oil	300–650	Medium	Fair to good	58
S2		Slow	1525–1575	10	Brine or water	300–800	Medium	Fair to good	60
S4		Slow	1600–1700	10	Brine or water	300–800	Medium	Low	60
S5		Slow	1600–1700	10	Oil	300–800	Medium	Low	60
S7		Slow	1700–1750	20	Air or oil	400–1000	Medium	Fair	59
T1	1500–1600	Rapid from preheat	2150–2300‡	2	Air, oil, or salt	1050–1150	Deep	Good	64
T15	1500–1600	Rapid from preheat	2125–2270‡	2	Air, oil, or salt	1000–1150	Deep	Fair	67
M1	1500	Rapid from preheat	2125–2175‡	2	Air, oil, or salt	1000–1150	Deep	Low	65
M2	1500	Rapid from preheat	2125–2225‡	2	Air, oil, or salt	1025–1150	Deep	Fair	65
M4	1500	Rapid from preheat	2125–2225‡	2	Air, oil, or salt	1025–1150	Deep	Fair	66
L3		Slow	1425–1600	20	Brine or oil	300–800	Medium	Good	62
F2	1200	Slow	1450–1600	20	Brine or water	300–500	Shallow	Good	66

*Based on AISI *Tool Steels Manual*, 1955, and modified by committee.
†Preheating necessary for complicated shapes and shapes of widely differing cross section.
‡Salt-bath basis.
Source: Frank W. Wilson, *Die Design Handbook*, New York, 1965. Reprinted with permission from the McGraw-Hill Companies.

TABLE 14-31 Typical Heat-Treatment Comparison Chart

SAE	Normalizing temperature, °F	Annealing temperature, °F	Carburizing temperature, °F	Cooling method	Reheated, °F	Cooling method	Tempering temperature, °F
1010–1022			1650–1700	A			250–400
			1650–1700	B	1400–1450	A	250–400
			1650–1700	C	1400–1450	A	250–400
			1650–1700	C	1650–1700	B	250–400
			1350–1575	D			Open
1024	1650–1750		1650–1700	E			250–400
			1350–1575	D			Open
1109–1120			1650–1700	A			250–400
			1650–1700	B	1400–1450	A	250–400
			1650–1700	C	1400–1450	A	250–400
1111–1113			1500–1650	B			Open
			1350–1575	D			Open
1320	1700–1750*		1650–1700	C	1400–1450	E	250–350
	1700–1750*		1650–1700	E	1475–1525	E	250–350
	1700–1750*		1650–1700	E			250–350
	1700–1750*	Yes†	1650–1700	E	1375–1425	E	250–350
2317	1700–1750*	Yes†	1650–1700	C	1475–1525	E	250–350
	1700–1750*	Yes†	1650–1700	E			250–350
3115–3120	1700–1750*		1650–1700	C	1400–1450	E	250–350
	1700–1750*		1650–1700	C	1500–1550	E	250–350
	1700–1750*		1650–1700	C	1400–1450	E	250–350
4317–4621	1700–1750*	Yes†	1650–1700	E	1475–1525	E	250–350
	1700–1750*	Yes†	1650–1700	C	1425–1475	E	250–350
	1550–1700*		1500–1650	E			250–350
	1700–1750*	Yes†	1650–1700	E	1375–1425	E	250–350

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4812–4820	1700–1750*	Yes†	1650–1700	C	1450–1500	E	250–350
	1700–1750*	Yes†	1650–1700	E	1375–1425	E	250–350
			1650–1700	E			250–350
5115–5120	1700–1750*		1650–1700	E	1500–1550	E	250–350
	1700–1750*		1650–1700	E	1425–1475	E	250–350
	1700–1750*		1650–1700	C	1425–1475	E	250–350
8615–8720	1700–1750*	Yes†	1650–1700	E	1475–1525	E	250–350
	1700–1750*	Yes†	1650–1700	C	1475–1525	E	250–350
	1700–1750*	Yes†	1650–1700	E			250–350
	1700–1750*	Yes†	1650–1700	E	1525–1575	E	250–350
	1700–1750*	Yes†	1500–1650	E			250–350
9310–9317	1700–1750*		1650–1700	C	1500–1525	E	250–350
	1700–1750*		1650–1700	E	1400–1450	E	250–350

A = cooling in water or brine, B = cooling in water or oil, C = slow cooling, D = cooling in air or oil, E = cooling in oil only.

*Air cooling to follow.

†Cycle anneal. Temperature to be identical with normalizing temperature. Rapid cooling to 1000°–1250°F followed by air cooling 3 hours later.

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TABLE 14-32 Heat Treatment (Hardening) for Carburized Steel (Refer to Fig. 14-14)

Treatment, steel condition	Condition of case	Condition of core
A, fine-grain	Refined, excess carbide not dissolved	Not refined, soft and machinable
B, fine-grain	Refined, excess carbide dissolved, austenite retention minimized	Unrefined, reasonably tough
C, fine-grain	Coarsened, excess carbide partially dissolved	Partially refined, stronger, and tougher than A
D, fine-grain	Coarsened, excess carbide partially dissolved. Austenite retention in high-alloy steel	Refined, max strength and harness. Better combination of strength and ductility than C
E, fine-grain	Unrefined, excess carbide dissolved, austenite retained, minimal distortion	Unrefined, hardened
F, coarse-grain	Refined, excess carbide dissolved, austenite retention minimized	Refined, soft and machinable, maximum toughness and impact resistance

14-7-3 Case Hardening

The case-hardening procedure is used to make the outer surface of a part hard while the core remains softer and keeps its toughness. For case-hardening of low-carbon steel, the surface of parts must first be exposed to the effect of the carburizing process to absorb an adequate amount of carbon. Only afterward these parts may be case hardened and quenched by immersion in water, oil, brine, and the like.

14-7-3-1 Depth of Hardened Surface. The desired depth of the case-hardened surface dictates the duration of the process and all its other parameters. With heavy or thick cases, exposure to case-hardening temperatures is longer, yet the maximum amount of carbon at the surface level is not found equally increased because the carbon's continuous yet slow seepage into deeper layers of the material is promoted by longer exposures to the case-hardening environment.

However, the actual linear depth of the hardened surface is a controversial subject, as the most influential factor in this sense is the size of hardened parts: Where 0.015 in. may be a heavy case on one part, 0.035 in. may be considered a light case on another.

When deciding on the depth of hardened surface, various aspects should be evaluated. These are

- Maximum permissible surficial wear of the part
- Amount of balance between properties of the core and those of the case
- Overall strength of the part after hardening

A heavy case must withstand quite heavy loading without succumbing to breakage and total collapse, since, if the case-hardened surface breaks, the inner core underneath will not have sufficient strength to sustain undue loading. The resistance to wear as well as to crushing may be attained by two basic procedures: Either a heavy case should be produced on a poorly hardenable steel, or a light case should be given to steel that will harden well even without any case. (See Fig. 14-14 and Table 14-32.)

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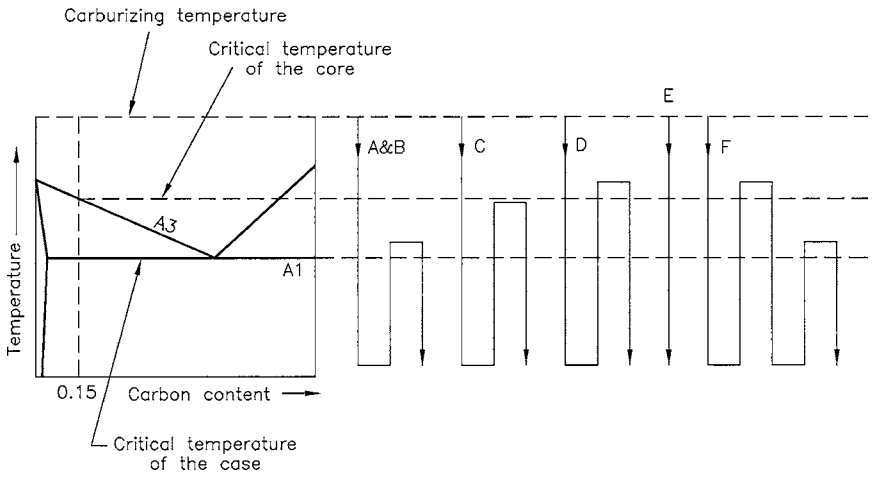

FIGURE 14-14 Hardening of carburized material.

Excessive grinding after the case hardening should be avoided, as it diminishes the hardened surface's thickness, wasting the expense of such treatment.

14-7-3-2 Pack Hardening. To prevent breakage of sensitive parts and to protect them from scaling while minimizing the danger of cracking or warpage, pack hardening is utilized. It consists of packaging the parts to be hardened into a carbonaceous material, which serves not only as their protection but also as a supply of carbon. For pack hardening, only the lowest temperatures should be used, between 1400 and 1450°F.

14-7-3-3 Surface Hardening in Liquid Baths. These may be cyanide baths, which are used where a very hard and thin case is needed on a low-carbon steel without producing shock-resisting qualities of the material. Other carburizing baths are of the sodium cyanide type. The advantage of surface hardening in liquids lies in rapid progress of a process, which also provides a uniform dispersion of carbon with a minimum of distortion and less nitrogen absorption. Portions that are not to be carburized may be protected by being copper plated.

14-7-3-4 Localized Hardening. This method is used where the parts are too large to fit the furnace or the bath, or where only certain portions of the product should be case hardened. Usually an oxyacetylene torch is used to heat the surface quickly; it is quenched afterward. Often tempering or drawing of the treated surface is recommended.

14-7-3-5 Induction Hardening. The induction-hardening cycle is short, often lasting only several seconds. The depth of a case and its area or amount of hardness are controllable, with no additional influences in the form of decarburization or oxidation. The best-suited parts for induction hardening are those of complicated shapes or those requiring only localized hardening. Also benefiting are parts such as cams which should be protected from distortion of their shape.

14-7-4 Annealing

Annealing is the opposite of hardening. It is used where stresses induced by previous cold-working operations are to be removed or where the crystal structure has to be refined, grain

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orientation reassessed, the hardness of the material lowered for subsequent machining, or mechanical and physical properties altered. Annealing is further used for removal of gases from the material and for changes in the material microstructure.

During the process of annealing, material is heated slightly above the

- Lower critical point for hypereutectoid steels, which are materials of greater than 0.85 percent carbon content
- Upper critical point for hypoeutectoid steels, which are materials of less than 0.85 percent carbon content

This temperature range is held for as long as the material pearlite structure needs to thoroughly dissolve and transform into austenite. Maintaining such temperatures also dissolves all available ferrite or cementite, turning them into austenite as well. The temperature range at which only an austenitic structure remains within the material is called the upper critical point (see 14-7-2 "Hardening"). After reaching such a range, the material is slowly cooled down.

Normalizing is an alternative of the annealing process, which is used to obtain uniformity within the part, free its structure of stresses, and restore proper grain size. Normalizing temperatures are somewhat higher than those used for annealing, the difference being usually 100°F. Parts are allowed to cool in still air at room temperature. The most often normalized objects are usually forgings, where a proper response to a subsequent heat treatment has to be ensured.

When normalizing precedes annealing for machinability, the process is called a *double annealing*.

Spheroidizing is used to obtain a spherically shaped form of carbide within the material. When spheroidized, high-carbon steels have their machinability improved, while the strength of low-carbon steel may be altered for subsequent heat treatment. Such a process also increases resistance to abrasion.

Stress relieving, or *aging*, is concerned with removal of the instability of material after quenching or with removal of strains imposed by cold working. Aging is performed at slow rates and parts are cooled at room temperatures. The change in material structure is followed by a change of its physical properties.

14-7-5 Tempering

Tempering, sometimes called *drawing*, is a method used for removal of both brittleness and internal strains from the hardened material. Tempering consists of heating of the material to the temperature of 300 to 750°F, at which its martensitic structure changes into slightly softer and tougher troostite. Additional heating to 750 to 1300°F produces another alteration within the material structure, turning it into sorbite, with much greater ductility, even though less strength.

The correct temperature range is judged on the basis of the color change of an oxide layer which develops on the material surface during the process of tempering. Such a layer forms on the surface of steel heated in an oxidizing atmosphere. Some basic colors and their corresponding temperature ranges are:

- Light yellow at 440°F
- Yellow-brown at 490°F
- Brown-purple at 520°F
- Dark blue at 570°F
- Light blue at 640°F

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Tempering is performed in oil, salt baths, lead baths, or sand. Oil tempering is used for the treatment of tools and the tempering temperature is limited to the range of 500 to 600°F. Salt baths run hotter, between 300 and 1100°F, and the possibility of temperature range control is greater, with much faster heating and greater uniformity in heat dispersion.

Tempering in a lead bath is used where both tempering and hardening are performed at the same time. To lower the melting temperature of lead, which is 620°F, tin is usually added to the bath.

14-8 SURFACE CLEANING

Metal parts, as manufactured, may contain residues of lubricants, shop dirt and dust, abrasives, splinters of materials, and a host of other impurities or contaminants. Often these parts have to be cleaned in order to prepare the surface for some other finishing process, such as painting or other coating application.

The proper cleaning method of such parts must be well chosen, with many factors in mind. First, the type of soil or contaminant to be removed has to be identified, since a different method of surface cleaning is needed for removal of grease than for metal chips. The surface requirements of the finished part must be taken into account in order not to use a method which may become detrimental to some special feature of the product. As an example, openings for certain sheet-metal hardware should *not* be deburred, as the roughness of one side is important for its installation.

Further, the problem has to be assessed with regard to the subsequent finishing processes, while bearing in mind the cleaning capacities of the particular company or plant.

There are several methods of parts cleaning, each using a different principle and each being applicable to a different range of cleaning applications. Some attack the elements to be removed by mechanical means; others use chemical compounds or steam or electrolytes or ultrasound, salt baths, and other variations. Main categories of these cleaning processes are listed below.

14-8-1 Mechanical Cleaning

Mechanical cleaning utilizes a mechanical action of abrasives and other objects, which are used in processes such as those of grinding, polishing, buffing, blast cleaning, or shot peening. Abrasive particles may be either dry or as contained in a liquid and applied against the surface of the part. Other objects used in mechanical cleaning may be anything from rags up to glass beads or buffing compounds.

This type of cleaning method may be used for removal of dirt, rust, flash, for deburring of parts, or just for roughing of the surface for subsequent finishing. The actual procedure depends on the particular part and the expected outcome.

Vibration cleaning is frequently used for small metal-stamped parts, where these are mixed with abrasives in the form of small stones or similar materials and placed in large drums, which are either vibrating or rotating. The simultaneous movement of parts and abrasive elements is capable of removing burrs, smoothing the surface, and to some degree finishing the edges and removing their sharpness. Larger-sized parts are deburred and surface-cleaned by an abrasive method of running them through an equipment which scrubs their surface by contact with an abrasive belt.

Blast cleaning uses abrasive particles, propelling them against the part to be cleaned. It is a cleaning method used with ferrous and nonferrous forgings and castings or to clean weldments, and so on.

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Shot peening differs from blast peening in that its cleaning action is merely an addition to its actual purpose of improving the fatigue strength of the material. This type of finishing is also capable of relieving tensile stresses that would otherwise produce stress-corrosion cracking. In shot peening, the objects propelled against the part are not of abrasive origin. They attack the surface by creating a multitude of shallow indents, which makes the process easily comparable to cold working of the material surface.

Cleaning of the surface with glass beads is used for parts of all sizes. As a cleaning method, it surpasses that using an abrasive slurry within a liquid. Glass bead cleaning may be utilized in preparation for painting, brazing, welding, and other similar manufacturing processes. It produces a matte finish, for which reason it may also be used for decorative purposes. A definitive advantage of cleaning with glass beads is that while the surface is being cleaned, no measurable amount is removed.

14-8-2 Alkaline Cleaning

The most often used industrial cleaning method is alkaline cleaning, the action of which is basically physical as well as chemical, aided by combinations of surfactants, emulsifiers, separating agents, saponifiers, and wetting agents all attacking the part to be cleaned. The solution may be heated or agitated in motion by stirring.

Dissolvable particles of dirt are washed away. Solid particles are separated from the part and allowed to either settle in the form of sludge to the bottom or be floated away and removed from the solution by means of filtering and similar procedures.

Alkaline cleaning may be used for removal of wax-type solids, metallic particles, oil, grease, dust, and other contaminants. The application of the process is by immersion in liquid or by spraying or emulsification. Such a cleaning process is often followed by a water rinse and a drying cycle.

14-8-3 Electrolytic Cleaning

This process is a specialized type of immersion cleaning, with the inclusion of electrodes within the process. A direct current is conducted through the solution, where the part to be cleaned serves as the anode while the electrode acts as the cathode. Some processes alternate the cathode-anode designation. The cleansing action of oxygen, which develops at the anode during the cleaning cycle, may further aid the operation.

This type of cleaning may be used for removal of rust, in preparation for phosphating, chromating, painting, and especially for electroplating, the latter demanding a higher degree of cleanliness.

14-8-4 Emulsion Cleaning

This process uses two basic materials, insoluble within each other, such as water and oil, combined with an emulsifying agent capable of forcing them to emulsify. This type of cleaning is used with heavily soiled parts, and the cycle is usually followed by alkaline cleaning for final removal of very minute contaminants.

Emulsifiers are of two types: (1) emulsifiers that aid the formation of emulsion which consists of a solvent in water, and (2) emulsifiers that aid the formation of emulsion which consists of water in solvent.

Frequently used emulsifiers are nonionic polyethers, hydrocarbon sulfonates, amine soaps, amine salts, glycerols, or polyalcohols. Solvents usually are of petroleum origin, such as naphthenic hydrocarbons (kerosene).

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14-8-5 Solvent Cleaning

This cleaning method consists of an application of solvents to the organic contaminants such as oils or grease, in an attempt to remove them from the surface of parts. Sometimes such cleaning has to be followed by an alkaline wash, in order to remove the solvent itself from the part surface. This type of cleaning may also be used for removal of water from electroplated parts.

Solvents may be either petroleum-based (such as naphtha, mineral spirits, or kerosene) or chlorinated hydrocarbons (trichloroethane, trichloroethylene, methylene chloride) or alcohols (isopropanol, methanol, ethanol). Other solvents include but are not restricted to benzol, acetone, and toluene.

The mechanism of cleaning is applicable mainly to contaminants of organic origin, such as grease or oils. These impurities may be easily solubilized and removed, or washed off the part's surface.

14-8-5-1 Vapor Degreasing. Vapor degreasing with solvents is a specialized branch of solvent cleaning. It uses chlorinated or fluorinated solvents for removal of soils such as grease, waxes, or oil. The objects to be degreased are placed within a tank, where a solvent is boiled. Objects are degreased by the action of vapors, which—being heavier than air—displace the latter from the volume of the tank. On reaching the upper cooler zones, these heated vapors condense and drip back down where they are reheated.

14-8-6 Acid Cleaning

Acid cleaning uses various solution containing organic acids, mineral acids, and acid salts, combined with a wetting agent and detergent for cleaning of iron and steel. Such a cleaning method may be used to remove oil, grease, oxide, and other contaminants without additional application of heat.

Acid cleaning and acid pickling are quite similar processes, with acid pickling being much more aggressive treatment, used for removal of scale from forgings or castings and from various half-finished mill products.

Mineral acids and salts are numerous, forming either inorganic (mineral) acid solutions or solutions of acid salts or acid-solvent mixtures. Organic components of these cleaning solutions may be oxalic, tartaric, citric, acetic, and other acids, with acid salts such as sodium acid sulfate, bifluoride salts, or sodium phosphates. Solvents used in this process may be ethylene glycol or monobutyl (and other) ethers.

14-8-7 Pickling

Pickling of metal materials removes the oxides, or scale, off the surface of parts. It may be used for removal of other contaminants as well, by immersing the parts in a liquid solution of acid. Such a solution may vary in its composition, temperature, and selection of ingredients, the most common pickling bath being sulfuric acid. Hydrochloric acid is utilized where etching prior to galvanizing is needed. For pickling of stainless steel, nitric-hydrofluoric acid is used.

The mechanism of pickling is that of a penetration of the scale through the cracks and chemical reaction of the pickling solution with the metal underneath. In order for the pickling solution not to attack the base metal, inhibitors in the form of gelatin, flour, glue, petroleum sludge, and other substances are added. Inhibitors can minimize the loss of iron surface and reduce the range of hydrogen embrittlement while protecting the metal from pitting, which may occur where pickling becomes excessive.

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14-8-8 Salt Bath Descaling

The salt bath descaling process is used for removal of scale and it must—for a complete removal—be followed by acid pickling or acid cleaning. Salt bath descaling may be divided into three groups: oxidizing type, reducing type, and an electrolytic method. The latter may be used even in conjunction with the previous two processes.

Oxidizing type of salt bath descaling is the most often used method of scale removal because of its simplicity, even though the electrolytic method offers greater scale-removing capabilities. The reducing method's advantage is lower temperatures of the salt bath.

The removed scale, along with the descaling salts, forms an insoluble sludge, which must be taken out mechanically. For that reason such impurities are allowed to settle into a pan placed there for their collection.

14-8-9 Ultrasonic Cleaning

Ultrasonic energy, when applied to the solution of chlorinated hydrocarbon solvents or to water and surfactants or to any other type of cleaning solution, will boost the cleaning process, removing various types of contaminants. It may be used for removal of fine particles embedded within the material, or for cleaning of complex parts, precious metals, or sealed units, and also for cleaning where extreme cleanliness is required.

The disadvantage of the ultrasonic process is its high cost, which is due to the much higher initial cost of the equipment and its maintenance. However, this type of cleaning has been found beneficial where previously only hand-cleaning methods worked.

14-9 SURFACE COATING

Surface coating should be chosen with regard to the application it has to serve, along with a consideration for the basic metal it has to cover. Some coatings are used as a protection against abrasion, corrosion, oxidation, and for a host of other reasons. Surface coating creates a barrier between the basic metal itself and the environment, sometimes detrimental to its stability. There are coatings to alter the frictional properties and to enhance the an aesthetic appeal of the part. Various coatings may be used for various applications but are most often chosen to protect the basic metal, the basic product, from outer influences.

Even two metallic parts within an assembly are capable of attacking each other by forming a galvanic cell, the same way a basic material may react adversely to its coating if chosen improperly. Evaluation of the possibility of a galvanic couple formation must therefore be considered when choosing the type and amount of protection a coating should offer. This involves a survey of whether the coating is in its nature cathodic or anodic toward the metal underneath it.

For example, a steel may be protected from other influences by nickel or zinc coating, even though nickel is cathodic to iron and zinc is anodic. Nickel protects the steel by successfully blocking the influence of the outer corrosive environment on the material, for the purpose of which, such coating must be free of pores. Zinc provides protection by corroding more readily than steel, and a by-product of the corrosive reaction, zinc oxide, being quite sizable, impairs the corrosive process and protects the coated material.

Many metals are capable of forming oxide films, which—when stabilized—act as a protective coating for that particular material. Aluminum oxides thrive in acidic atmospheres, where they form thick protective layers, but once the basic alloy is anodized, the coating

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shrinks, turning thin, hard, and stable. Some oxides, such as those of tin, zinc, titanium, and others, could be stabilized by an additional chemical or electrochemical treatment, which will turn them into protective layers for the basic metal material.

The success of such protection depends on proper analysis of the galvanic-cell process, during which an anodically dissolvable metal must be protected by an equal and opposite cathodic reaction.

14-9-1 Electroplating

The electroplating process should actually be called galvanizing, since it uses the principle of a galvanic couple between the plated part and plating material to transfer particles of material to the surface of the part. In this process, a direct electric current is applied to a solution of metal salts in which the parts to be coated are deposited. These parts assume the role of the cathode, or negative pole, by being connected to the negative end of the source of energy. Large parts are left hanging off a copper bar attached to the negative pole of the source, and small items, such as washers or bolts, are placed in wire baskets. The coating metal itself acts as an anode, and it is added to the bath in the form of plates, bars, or extruded shapes.

When affected by the electric current, the anodic metal material slowly ionizes, its particles entering the solution of the bath. These little ions travel toward the cathodic-polarized part, on whose surface they become deposited in the form of metal crystals. Some types of metal-coating processes require coating baths to be heated and sometimes a liquid-stirring action is added to enhance the uniformity of the film.

The speed of the development of coating depends on the intensity of electric current and temperature of the bath. With a warmer bath or with higher amperage of the current, the coating process becomes faster. However, with too high an intensity or with too warm a solution, the coating emerges coarse and inadequate. The electric current has to be low in *voltage* (often few volts will suffice), but the *intensity* must be quite high, with 0.1 to 2 amperes or more per each square foot of the coated surface.

Organic compounds are sometimes added to the bath and their minute quantities alter the properties of the coating film to a considerable extent. Their influence is oriented mostly toward an aesthetic appearance, with subsequent smoothing of the coated surface and providing it with a sheen. These strictly optical enhancements are outweighed by a diminished protection against corrosion they offer.

Almost all metals can be galvanically applied as coatings by using modern methods and modern technology. However, with some, the process is so costly that it remains only a technical curiosity.

The four most common processes of galvanized coating are

- Acidic galvanic coating, in which the metal is present as a cation in a simple salt solution, such as that of sulfates, sulfamates, fluoborates, or chlorides. This process is used for the application of nickel, copper, zinc, and tin coatings.
- Complex alkaline cyanide baths, with the metal particle in the form of an anion, connected to the cyanide portion of the solution. This type of bath is utilized for application of copper, cadmium, zinc, silver, and gold coatings.
- Complex acid baths, where the cathodic deposition is achieved through an intermediate stage, or as a cathodic film. An example is chromic acid, which forms mono- and dichromate ions.
- Alkaline baths for metals, forming amphoteric oxides, such as alkaline stannate bath, which contains sodium or potassium stannate, stabilized by ions of hydroxyl.

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Parts to be coated by electrodeposition must be deburred, cleaned, and their previous coating—if any—completely removed. For better adherence, pickling or acid dip may be used. The cleaning process is vital to the success of the plating operation, because a maximum adhesion of the coating to the basic metal is necessary.

Copper electroplating is usually used as a bottom layer for additional plating. Rarely is copper used alone as a coating material, since it scratches and stains readily and tarnishes from weathering. If a bright copper surface is required, it must be protected by at least a coat of clear lacquer. Copper is usually plated in cyanide baths or in acid plating baths.

Chromium electroplating, or industrial chromium plating, is corrosion-resistant and extremely hard. It differs from decorative chromium plating in that industrial-type deposits are applied to the basic metal without intermediate undercoats. Industrial chromium plating is intended only for the protection of parts, for extending their life in service by shielding them from wear, corrosion, or heat effects. This type of deposit, as opposed to decorative chromium plating, is also thicker, ranging from 0.1 to 20 mils, whereas decorative chromium plating uses thicknesses of 0.005 to 0.05 mil.

Hard chromium plating is being widely applied to various types of tooling, in which case the coating extends the life of the tool, improves its performance, or even repairs worn out surfaces. By the application of hard chromium coating to injection molds, these tools are protected from the destructive effect some plastic materials (i.e., vinyl) may have on the metal material of the mold. Cutting tools, deep drawing tools, various machine parts, and other products may greatly benefit from the chromium plating. However, with parts exposed to high heat and pressure, chromium coating will not perform well, as it may crack in service.

Nickel electroplating may be produced in Watts baths or in sulfamate or fluoborate baths. Nickel plating is one of the oldest surface-protecting metallic coatings of steel because of its good appearance, combined with resistance to corrosion. Today, these coatings are used for protection of iron-, copper-, or zinc-based alloys against corrosion.

Cadmium electroplating serves as a protection against corrosion as well. Cadmium, being anodic to iron, conserves the basic ferrous material even when scratched or otherwise damaged. Aside from acting as an anticorrosive layer, cadmium coating has lubricating properties, considerable electrical conductivity, and low contact resistance.

Tin electroplating allows for thin layers of tin to be used as a protective barrier against tarnishing and corrosion, while enhancing the solderability of coated material. The bulk of tin plating applications was reserved to the mass-packaging of food, where it was used as a liner for steel cans. In the absence of oxygen, tin protects the food within the cans from coming into contact with the material of the can. Lately, the tin deposit in food cans was replaced by plastic coating. Another usage of tin plating is in the electronic, agricultural, and transportation industry.

Zinc electroplating offers a suitable surface protection for materials with low melting point, such as iron or steel. Zinc is a nontoxic metal and the plating process is relatively inexpensive, offering an excellent protection from weathering and corrosive influences, in which way it surpasses nickel coating. In heavily corrosive environments, such as marine applications, zinc is outperformed by cadmium. However, with the worldwide-progressing ban on cadmium plating, alternative resources, such as alloyed zinc coatings, are being investigated.

Miscellaneous plating materials include silver, gold, brass, and bronze among others. Plating with combinations of metals, or alloy-plating, is a modern attempt at the greater control of the result, aiming at the reduction of the progress of corrosion. Alloyed coatings may be zinc-iron, zinc-cobalt, zinc-nickel, zinc-lead, and other. Zinc-nickel coating is found widespread in the modern fastener, automotive, and communication industry, where it is utilized in some heavily corrosive areas. The protective coat of zinc-nickel plating was found capable of preventing the basic metal of a fastener from forming a galvanic corrosive cell with aluminum, which possibly opens a new field of application within the airline industry. Zinc-cobalt coating displays a tremendous resistance to atmospheric influences, even to those enhanced by a greater content of sulfur.

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14-9-2 Electroless Plating

Electroless plating uses no electric current. The plating procedure of electroless zinc plating, for example, consists of depositing the plating material by means of an autocatalytic chemical reduction of zinc ions by hypophosphite, aminoborane, or borohydride compounds. There are two types of baths for electroless plating: (1) hot acid baths, to plate steel and other metals, and (2) alkaline baths, for plating of plastics and other nonmetallic materials.

Nickel plating provides the basic material with excellent protection against corrosion. Where applied to aluminum, nickel plating provides a solderable surface.

Zinc plating is attained in cyanide baths, alkaline noncyanide baths, or acid chloride baths, the latter being the fastest-growing method of plating.

14-9-3 Hot Dip Coating

The hot dip method of coating uses a bath of molten metal material to dip the objects to be coated in. Often, this method is called "hot dip galvanized coating" in the literature, where the word "galvanized" is not correct. Galvanizing always refers to the process, which is implementing a galvanic cell within the principle of the operation. With the galvanic cell, there is always an electric current involved as well, which—in hot dip coating—is not present.

The temperature of the bath, combined with the length of immersion, govern the speed of coating application. The visibility of the crystal like grain of the solidified coating, which often "decorates" its entire surface, may sometimes be optically disturbing.

A thorough cleaning of objects to be dipped is required. All products must be cleaned to be free from grit, oils, and grease, drawing lubricants, and other contaminants, to ensure a proper adherence of the coating to the basic metal.

Hot dip zinc coatings are readily attacked by sulfur dioxide and other industrial pollutants, and for that reason their longest life expectancy is in rural areas where industrialization is not yet widespread.

Hot dip tin coatings when applied to the cast iron or steel provide the basic material with a nontoxic coating, often used in the food-processing or electronics industry. Decorative coatings of the hot dip type are also common. The tin coating improves solderability of the basic metal and can be used as an adhesion promoting agent with subsequent coatings.

Hot dip lead coatings usually employ lead-tin or antimony combinations to coat washers, bolts, and other mounting hardware, and small metal-stamped parts, such as brackets, plates, and various fixturing elements. Lead alone is not capable of combining with iron into a coating, as it either separates into free lead crystals, or turns into a fungus-resembling layer.

Lead-tin alloys form a layer of excellent adhesion, which acts also as a lubricant, an agent to improve solderability, or just a protective barrier against corrosion. This type of layer is called a *terne coating.* Two kinds of such surface protection are used widely: *Short terne,* which is very light in thickness (0.01 in.), and its thicker equivalent, *long terne,* ranging between 0.01 to 0.08 in.

14-9-4 Chemical Coating Processes

These types of coatings provide the part with the surficial layer of mostly nonsoluble salts, a result of the chemical reaction between the material of the coated part and the chemical components of the bath. The acidic bath attacks the metal surface, dissolving the most outer layers and turning them into ions, which readily combine with the chemical content of the bath. Inorganic and marginally also organic salts constitute the basis of the bath, their action being supplemented by activators or oxidating agents.

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Parts to be coated are allowed to remain immersed for a certain period of time. They must be thoroughly cleaned, often pickled, free from grease, oils, and other contaminants. Complexity of the shape presents no restriction, as the chemical reaction takes place simultaneously over the whole surface, whenever the bath solution gets into contact with it.

Chemical coatings do not provide the parts with the best corrosion or abrasion protection. The coating is limited in thickness and it is useful mainly with small parts, for those with very accurate dimensions, or where the equal distribution of coating over a complex surface is important, such as with objects containing an inner thread or other types of complex crevices. The coating can be easily damaged by mechanical means. For these reasons, chemical coatings are the best used in conjunction with other coating processes, as adhesion promoting layers with subsequent coatings, especially with paints.

According to the process used, chemical coatings can be divided into several categories: chromating (chromate conversion coating or passivating), phosphating, and oxidating.

Chromate conversion coating. Parts, as immersed in an aqueous solution of chromic acid or chromium salts (sodium or potassium chromate or dichromate) or in various other acids combined with activators and modifiers in the form of chlorides, fluorides, sulfates, complex cyanides, and phosphates, form their own protective coatings within their surface. Such a coating is actually the material's response to the chemical attack of the bath. It is composed of nonsoluble metal salts, obtained by a partial dissolution of the material surface and their combination with the chromate ions of the bath.

Metals such as zinc, magnesium, tin, and aluminum may be coated this way for protection against rust or corrosion. There are two forms of chromate conversion treatments: (1) those providing a film of their own on the material's surface, and (2) those supplementing or securing another type of nonmetallic protective coating, such as that of oxide or phosphate.

Chromate conversion coatings may be colored or clear, the colors being influenced by the type of modifiers and accelerators in combination with the basic metal material. For example, fluorides and sulfates will produce a bright blue film on an electroplated zinc material, fluorides and ferricyanides will result in a gold film on aluminum.

Passivating. The possibility of forming a protective layer of its own is a sign of passivity of a material's surface, or its ability to remain unaltered in appearance, even though being subjected to corrosive attacks of its surrounding. Because most conversion coatings dissolve very slowly in water, passivation serves as a simple means of protection against corrosion in milder or indoor environments.

Phosphate coating is a method of surface protection for steel or iron consisting of an application of diluted phosphoric acid and its salts, combined with metals (zinc or iron or manganese) and other chemicals, to the surface of material. The reaction between these elements and the base metal produces a layer of insoluble crystalline phosphate at the interface, capable of protecting the material from abrasion by mechanical means or atmospheric corrosion.

This type of coating is also used as a base coating for further application of paint or additional corrosion-resisting material. Phosphate coating also provides the surface with lubricity and with protection against wear and galling.

The three principal types of phosphate coatings are distinguished according to their additives as those using zinc, iron, and manganese. Zinc phosphate coating varies in colors and their intensity: The higher the carbon content of the material, the darker the hue. Iron phosphate coatings have excellent adherence to the basic material, which they protect from flexing when painted or from flaking under an impact. Manganese phosphate coatings are used for bearings, gears, and similar to prevent galling.

After the treatment, the remaining phosphate is rinsed off with water, which must be free from chlorine or sulfates to avoid an attack on the fresh protective layer.

Surface preparation for phosphate coating should be very thorough, as the chemical reaction between the basic material and the phosphating solution depends on the amount of contact between them.

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Chemical oxidizing is a process similar to chromating and it is sometimes quite difficult to distinguish one from the other. In oxidizing baths, a surface coating, consisting of oxides of the coated metal in conjunction with other ingredients of the bath, is formed. Chemical oxidizing sufficiently controls the stability of the aesthetic appearance of parts exposed to the indoor pollution. Combined with an additional paint, oxidation is a valid barrier against the general atmospheric corrosion. It is reserved for smaller objects made of aluminum and aluminum alloys, or for objects with a long shelf life, for those with very close tolerances, optical devices, and firearms.

14-9-5 Anodizing

Anodizing may be defined as an electrolytic process which produces a thickening and stabilizing of oxide layers within the surface of the base material. Anodizing provides the coated part with wear, corrosion, heat, and abrasion resistance. A film created by anodizing serves also as an electrical insulator.

The method of coating consists of immersing the part to be anodized in an electrolyte (a 15 percent solution of either sulfuric acid or various organic acids), to which an increasing voltage is applied. The current is usually direct, but may also be alternating. It converts the immediate surface of the anode, which is the part to be coated, to an oxide. This oxide is electrically nonconductive and being almost nonsoluble in the electrolyte, it remains attached to the part, forming a continuous, solid coating. The bulk of such a layer automatically slows down and finally stops the additional electrolytic process, for which reason the coating of anodized objects can be produced up to a specific thickness only. The thickness of anodized coating is uniform throughout the part, regardless of the complexity of its shape. It is being developed from the outside toward the core of material and its thickness is always greater than that of the original layer of material, utilized for its development.

The anodized surface can further be altered in appearance prior to sealing, since the oxide pores are still open and able to absorb various colloidal substances, such as coloring agents or hydroxides of metals. Dyes, when combined with specialized anodizing procedures allow for attainment of various colors, or imitation-look of pewter, copper, bronze, and other special finishes. Unfortunately, corrosive influences may attack such a part; therefore the oxide pores must be sealed for the protection of the coating.

Various techniques can be used for sealing the anodized surface. For a clear finish, boiling in deionized water converts the amorphous form of aluminum oxide to a more stable form of crystalline hydrate. To improve corrosion resistance, a dichromate sealing method is used; a color-stained anodized surface must be sealed in nickel acetate to prevent bleeding.

The anodizing process is not restricted to aluminum; it can be applied to other light metals such as magnesium, titanium, and their alloys. The hardness of an anodized coating equals that of a diamond, making this type of surface finish an excellent barrier to corrosion, providing the parts with wear and abrasion resistance, and enhancing the aesthetic appearance of the parts.

14-9-6 Thermodiffusion Process

Coatings produced by thermodiffusion are formed at high temperatures and in controlled atmospheres of specific content. Diffusing materials of gaseous, solid (powder), or molten form are placed in contact with the part to be coated and allowed to enter its surface. The coated material, usually steel or iron, forms an alloy with the diffusing components within the upper layers of the coated surface. The coating emerges uniform in thickness throughout the part.

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The temperature of the process is somewhere near the melting point of the diffused metal and the heating procedure is conducted in an oven. Various processes use different temperature settings: These are either below or above the melting point preferences, according to the diffusion substance used. The temperature of the process influences not only the speed of the coating operation, but also the character and texture of the finish as well.

The most common thermodiffusion processes are cementing and nitriding, but other applications utilizing chromium, aluminum, sulfur, and zinc are being widely used. With zinc, the process is called *sheradizing,* and the metal material is added in the form of powder. With the melting point of zinc at 786°F, sheradizing is usually performed at temperatures ranging from 600 to 700°F. Thermodiffusing of sulfur is performed along with nitrogen, and the process is almost the same as that of nitriding.

Newer diffusing processes, utilizing boron and silicon, were developed for attainment of an extra high surface hardness, abrasion and wear resistance, and resistance to high temperatures. Another new technique involves a combination of the thermodiffusion process with electrolysis of the salt melt.

Thermodiffusion is preferred as the surface treatment of small parts, since a distortion of products and their dimensional alterations may occur with larger objects. A considerable variation in wall thickness or sharp corners on the part will magnify these complications.

14-9-7 Thermal Spray Coatings

Thermal spray coatings are applied at high temperatures, using a high-velocity stream of compressed air or gas in combination with an electric arc, plasma arc, or arc flame. The coating material is melted by the temperature of the heat source and propelled against the coated part. This process is often called *metallizing.*

The coating material is supplied in the form of rods, wires, or powder. After its melt is force-deposited on the coated surface, it is retained by either becoming embedded in the material, or by bonding with it through the process of either diffusion or alloying. A possibility of a combination of all three retaining methods within a single coating process is probable.

The thermal spray method is not restricted to coating with metals; ceramic materials, or those of combined metal-ceramic content can be utilized. Mechanical properties of the coating material change on thermo-deposition, since it turns into a hard, brittle, and nonhomogeneous layer of metals and their oxides, with only marginal tensile strength and a great resistance to pressure. Such a coating offers less protection against corrosion since the thermal spray coating process produces layers perforated with open pores.

The thermal spray method is employed where electrical resistance, or electrical conductivity, or electromagnetic and thermal shielding of the part are required. The attainment of either of these properties depends on the coating material and the coating process used.

14-9-8 Vacuum Coating

Vacuum coating is applied using three basic techniques of the coating material disintegration: evaporation, ion implantation, and sputtering. The appliable condition of metal is achieved with the aid of electron beam or ion beam gun, resistance or induction heating, plasma discharge method, or electron-emitting arrangement.

Evaporation using vacuum coating process is conducted in the vacuum of 10^{-2} Pa or greater, where the coating material is heated by either resistance or induction heating process or laser beam application, up to its melting point. The object to be coated is purposely kept

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distanced from the source of heat to remain colder. Evaporating gases condense on the colder surface of the part to be coated covering only those portions exposed to their influence. The thickness of coating can be well regulated, and for the best adherence of the film, parts must be thoroughly cleaned and sometimes even pretreated, especially where thicker deposits are desired.

Almost all metals can be used as vacuum-applied coatings, even though practically the process is restricted to aluminum and chromium and some of their alloys, selenium, germanium, selected oxides, and fluorides. Coated materials can be almost anything as well: metal, glass, aluminum, paper, and other. Vacuum coating with aluminum is selected for its high gloss, used for production of reflective surfaces in reflectors. Vacuum coating is irreplaceable as a costume jewelry coating and in other decorative applications, along with a heavy involvement in electronics industry.

The *ion implantation method* is employed for complex-shaped parts, and it uses a bombardment with high-energy ions, produced in a glow discharge of the gas. The part to be plated is conductively attached to a high-voltage electrode, insulated from its surroundings. A negative current of 3 to 5 kV is used in this process, as applied across the electrode, with the ground connected to the system.

At the beginning of plating process, the plating chamber is pumped down to 10^{-3} or 10^{-4} Pa and then partially refilled with a controlled amount of argon, to a vacuum of approximately 10^{-2} Pa. At the application of electric current, the part is first bombarded by ions of argon, which clean the surface for further processing. By adding the vaporized coating material into the glow discharge, it is propelled against the coated part. The coating film produced by this method emerges uniform in thickness, no matter how intricate a shape the coated part possesses.

Sputtering also uses a heavy inert gas, most often argon, in a glow discharge for the bombardment of the coated surface. As with ion planting, the chamber is evacuated and refilled with argon until reaching a desirable vacuum. The coating material is considered a cathode, receiving a negative bias from the high-voltage source of energy, which is supplying the process with 1 to 5 kV. Positive plasma ions are accelerated by the high-voltage electricity and sputtered against the cathode, striking and ejecting it against the coated part.

With such a method of coating, almost any material can be used to produce the film, as its turning into a vapor phase is achieved by mechanical (exchange of momentum), rather than electrical or other means.

14-9-9 Painting

Painting is an application of a thin layer of organic coating (liquefied or as a paste) to the treated surface. Paints may be separated into the following groups:

- Waterborne paints, or those which are dilutable with water. These may be solution coatings, based on water-soluble binders (alkyds, acrylics, epoxies) or colloidal dispersions (small elements of binder material, dispersed in water) or emulsions (latex).
- Enamels, forming a smooth, high-gloss surface. They may be dried in air or cured in an oven.
- Lacquers, or synthetic thermoplastic materials, capable of creating a film soluble in an organic solvent.

Painting has certain advantages over other coating processes. Paints are easy to apply, the necessary equipment is less costly, and a wide variety of pigments allows for easier matching of a hue, while the coating itself protects the basic material against different types

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of corrosive influences. Paints can prevent an emergence of galvanic corrosion between dissimilar materials. Many pigments contained in paints are conductive enough to offer protection against static electricity.

14-9-10 Porcelain Enameling

This process is applied to steel or cast-iron material. It is essentially a glass coating, which must be matured in the oven at higher temperatures of approximately 800°C. Porcelain enameling of aluminum or copper is rare. If enameled, aluminum cannot be heated to such a high temperature, with 580°C considered adequate.

The process of porcelain enameling starts with an application of frits to the surface. Frits are smelted complex glass or ceramic materials in an aqueous solution. Some types of frits are applied in their powdered form, in which case an electrostatic spraying is the method of their application. In spite of considerable content of metallic oxides, these materials behave similarly to glass; they are brittle, display a great resistance to chemicals and higher temperatures, and have a limited resistance to thermal or mechanical shocks.

After being treated with frits, parts are placed in an oven and heated to the desired temperature. Most often, a single coat, preceded by a base coat of limited spectrum of colors, is produced. The top coat may be opaque, in which case it is mostly white. But pigmenting for a wide array of colors is possible and clear or semiopaque coats can be attained as well.

The design of enameled parts must take into consideration the coating process and its demands: All corners must be rounded, with small-sized radii totally excluded, and a too diverse combination of surfaces avoided. With thicker enamel coatings, the requirements are still more demanding.

Porcelain enameling offers an excellent protection against abrasion and corrosion, coupled with greater than normal weather and chemical resistance. Enamels can resist an attack of acids even at higher temperatures. However, they can be affected by phosphoric acid or by fluorides.

14-9-11 Miscellaneous Coating Techniques

These include, but are not limited to, various methods listed below.

The chemical vapor deposition method is a process similar to carburizing. In this method of coating, a reactant gaseous material is introduced into a heating chamber, where a part to be coated is deposited. The gas is then allowed to settle and decompose upon the part's surface. The coating material, admitted in a gaseous form as well, becomes absorbed by the surface of the coated part.

Reactant atmosphere consists of fluorides, chlorides, bromides, hydrocarbons, and other compounds. The coating materials used in chemical vapor deposition coating are

- Chromium, which is used for steel and its alloys, and the coating process resembles that of pack cementation.
- Tungsten, used most often with ferrous alloys and iron, and requiring a nickel undercoat.
- Nickel, a coating used for plastic molds or for specific inaccessible areas.
- Titanium in the form of titanium carbide or titanium nitride is useful for coating of cemented carbide inserts, threaded parts, various types of tools, and other small items.

These coating are used mainly for prevention of wear and corrosion of the base material.

Babbitting consists of attaching a layer of softer metal (usually a tin-lead composition) to a part of much sturdier composition which acts as a supporting element. The soft layer, or the babbitt, has excellent antifrictional properties. In shafts, the babbitt averts galling and scoring of the surface, while the inner, stiff core acts as its support in torsion, when rotating.

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Babbitting is used with bearing shells, hardware elements, automotive connecting rods, jewelry, and numerous other applications. The babbitt is attached to the supporting metal by either of two methods:

- Mechanical bonding of babbitting is performed by using fasteners, dovetails, and other grooves.
- Heating of the babbitting material along with its supporting part and allowing the assembly to first cool at the area of contact between the babbitt and its support. This method is useful with shells, where the babbitt is introduced in the form of a mandrel.

Electropolishing acts almost like etching, and it can smooth the metal surface by anodic means, using a concentrated acid or alkaline solution for removal of burrs produced by conventional machinery, or for improving the appearance of the parts and enhancing their resistance to corrosion. The process can be further expanded to prepare the surface for subsequent coating, to improve reflective properties of parts, and to remove stressed or distorted surficial layers. Electropolishing is used for surface treatment of turbine blades, surgical instruments, nameplates, reflectors, jewelry, watch cases, piston rings, valves, ornaments and trims, and many other items.

Coating with plastics. Plastics can be applied in the form of foils, paints, bonded and baked-on layers, or shrink-wrapping elements. Plastic coats are usually quite bulky and their use is reserved for specific situations only.

For coating with plastics, a method called *powder coating* is often utilized. It employs plastic powders that are deposited on the surface of parts in ambient environment, using specialized spray guns. Due to static electricity, plastic powders remain attached to the metal substrate and is eventually baked to it. Powder coatings are often indistinguishable from painted coating, the only telltale sign being their greater thickness.

Cladding, otherwise called a solid-to-solid diffusion, is based upon diffusion of various solid materials such as metal laminates or composites. Aluminum cladding is used for mild steel and aluminum alloy. Nickel cladding on steel is advantageous, because the ductility and thermal properties of both materials are similar. Stainless-steel cladding to carbon steel is aided by electrowelding or by hot pressing or casting. Copper cladding of steel may be attained through casting, and it is particularly applicable to cladding of wire and tubing.

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CHAPTER 15
DIE COST ESTIMATING

15-1 TRENDS IN SHEET-METAL MANUFACTURING

Metal stamping and sheet-metal production are constantly growing technologies. True, there have been tendencies to replace many metal parts with plastics, since the cost of dies is sometimes considered too high. (As if the cost of molds were lower!) However, these tendencies will probably be somewhat balanced in the future, when manufacturers will finally realize—by adding up numbers on paper—that plastics cannot always replace sheet metal nor may sheet metal always replace plastics.

Everything has its own sphere of usage and application. Plastics are great materials, yielding, permissive but easily deteriorating, changing colors, crumbling away under the effect of either sun and weather or time. Sheet metal, once a part is made of it, remains stable without being affected by time, environment, an operator, or anything at all, with the exception of hammers and corrosives and extreme heat, of course.

A great advance in sheet-metal work was accomplished by implementing numerically controlled machinery like automatic drill presses, automatic punch presses, and lathes. These manufacturing tools are real workhorses, hurling out products of superior quality and continuity. Naturally, this is true only if the programs they run on are of an equivalent quality.

The discovery of EDM machinery was another step forward, as these machines, quite unheard of several years ago, quietly and efficiently produce parts previously considered impossible to make. Additional new technologies emerge on the market continuously, many of them quite beneficial to the manufacturing field, many still controversial. Lasers, plasma technology, electroerosion, chemical erosion, electrospark coating systems, anodomechanic machining, electroresistant machining, ultrasound application, pressure-waves fabricating (explosives)—all these new manufacturing processes are here to make our lives easier and more productive.

The number of innovations within the manufacturing field has been tremendous, considering that a host of the new methods mentioned did not take long to arrive in our shops. They are quite numerous and their technical advancement superior. Where before we could have a simple little press with limited controls and a manually lowered safety grating, we now show off programmable, fully controllable, and fully cooperating machines.

It almost seems that if we go ahead at this rate, we shall soon live in a utopia where machines do our bidding and we are finally able to devote more time to areas so far neglected because, even though important, they were not considered profitable.

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15-2 BASIC APPROACH TO COST ESTIMATING

In order to fit comfortably within the new world of technical modernization, we must create a completely new approach to various supportive factions of the industry. Many aspects to consider may not be strictly technical, yet they are essential to the overall outcome of the manufacturing process. These are mainly planning, inventory control, advertising, selling, and naturally—cost estimating.

Fortunately we have some excellent manufacturing-related computer programs which allow for production planning and scheduling of quite complex operations. They keep track of numerous bills of materials, consisting of myriads of components stored within a dense forest of shelves. The mind of a computer, if it has any, can easily sort its way out of such chaos and instantaneously find the correct procedure to follow, correct papers to issue, or the proper parts to send to the production line. On the basis of existing production rate, it warns us when the stock is getting low or when deliveries are exceeding the rate of usage. It shows the numerous locations where a particular item is used. It alerts us to a change of design, a change in manufacturing method, a change in delivery, and any other change at all. It actually does all the work of technical aide to the designer/engineer/production team.

Computers are capable of incessantly aiding the manufacturing process, the administrative process, bookkeeping, planning, inventory control, and a host of other pertinent segments within an industry. They achieve this complex task by aligning various data, matching results, sorting information, and grouping it, listing it, and referencing it.

But how would even the most advanced computers aid a process where no data is stored, no records of previous operations accumulated, and no procedures to follow outlined? This is basically the existing condition of the cost estimating field at many current industrial enterprises. This portion of manufacturing did not always advance as readily as other sections; it took upon itself the role of "sleeping beauty" who is still waiting for someone to awaken her.

Over the years, people within the manufacturing field came up with many ideas on how to estimate the cost of a new work, but their methods were either too complex or too tedious or too inaccurate. Where some estimating methods worked well, these were probably kept secret, since a well-functioning estimating procedure is equal to real money in the bank.

The method of estimating the product's cost on the basis of projected sales outcome may work, and it may fail at the same time. What is true today may not be true tomorrow, and we can hardly predict sales revenues for next year when we don't know if the product will sell at all. Today, if everyone's buying tractors, who knows if they will keep on buying them next year? Perhaps they will, perhaps they won't. It all depends on the saturation of the market with that particular product. It also depends on the accessibility of funds, on the exchange rates, on the company's solvency, on the amount of enthusiasm of its leaders and employees, and on many other subtle or obvious aspects, which govern every financial decision of every firm, person, or government.

A basic lesson of economy maintains that every product has several stages of its useful life. First, there is the phase of development, followed by advertising and the product's introduction into the market. Then, ideally, sales picks up and the plotted line goes straight up at 45° or a steeper angle if possible, until a large curve bends it down again. The top of such a curve, or the peak of that part's performance as a salable item, marks the saturation point within the segment of population consisting of applicable buyers. From then on, there will be nothing but a decline, usually gradual but quite sudden if a new and more appealing object of the same category emerges, replacing the old one.

Some speculate that there is a possibility of taking off the peak of the line with another 45° (or steeper) line, representing a market established in a different part of the world. They believe, where a market is declining in one corner of our little global plantation, the other corner of the world may have a genuine interest in such a market's implementation. This is

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true, naturally, if the world is staged as found today: Some nations are better off, some are more developed, other nations are not so much advanced, and some are outright backward. Naturally, all backward nations will gladly purchase a useful item even though it has completed its life cycle within the more advanced world of developed countries. This means that—provided these people have means of payment—and provided we have the means of supplying them with that particular item, we have a deal.

But what happens once all nations are on the same level? Where will we find additional dump grounds for our overexploited or unutilized stock? Who will buy an item which does not sell at home anymore, when "home" is the worldwide term?

Some are preparing for this situation by outpricing their competitors, meaning lowering their own prices. There are now various means of lowering prices. Products may be manufactured elsewhere, where the cost of labor is low. Products may be manufactured from inferior materials, the design may be cheapened, or a company's profit may be slashed, temporarily. Yes, there are means of lowering prices, but who will guarantee that such means are not lowering the salability of the particular product as well? What if nobody will ever pay $12 for an item they could previously purchase for $3?

In its extreme, such an effort may result in dumping of products upon a foreign country's market, paying all the exporting/importing costs and duties, and still charging a lower price than a local manufacturer. This is not a fantasy; it's an often encountered reality.

However, it may be stipulated that lowering a price is a relatively feasible approach to capturing the market. But with respect to what are we lowering it? What are the criteria for any existing price range anyway? The manufacturing cost plus the profit margin plus overhead? Certainly not! At least not always and not everywhere. Sometimes a tiny pill two times a day may cost several times its weight equivalent in gold.

But markets have been created and prices have been set, and actually we don't even know if the price ranges are correct. For, should we—for example—show a brand new product to some people, explain its function along with its advantages, and ask how much they will pay for such an item? Without a doubt, we will get a whole range of prices, and perhaps none of them will be in the vicinity of the actual cost. A $12 item may be assessed at $80, and a $1200 article may be valued at $120. The sky is the limit; prices may fluctuate incessantly and—what's worse—uninformed people will be willing to pay them.

Because of prices' fluctuation and also because of their frequent nonrelatedness, it often helps to assess costs rather by percentages instead of assigning them actual monetary values. Especially when using a computerized approach, formulas may be implemented and stored in the computer, and once an actual numerical input is added, the system will come up with a whole range of variations.

15-2-1 Pricing History

For obvious reasons, the most important commodity in cost estimating is the price history of each particular item. Usually, when figuring the cost of a part or product, estimators tend to send out numerous requests for quotation, eagerly awaiting the answers, which they add up to obtain the cost of the item. This method, even though it works in the short run, is actually disaster-prone, because when one or more manufacturers do not submit their proposals, what numbers will the estimator use in the absence of the object's pricing history? Or—what if only one manufacturer who always comes up with the highest cost responds? It will be risky to use that quote, because the price will be too high then. It will be equally risky to lower the price, because what if the other respondents didn't quote because they were not able to price the item within their usual cost range or because they were not able to manufacture it at all?

Therefore, every estimator should strive to accumulate his or her own pricing history of each quoted product. For example, Table 15-1 shows estimates five vendors submitted over a 5-year span. This is valid information, which may be assessed in several ways.

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TABLE 15-1 Cost-Estimating History

Vendor	Jan 01	Jan 02	Jan 03	Jan 04	Jan 05
First	$3.25	$3.65	$3.65	$4.80*	$3.95
Second	$3.75	$4.20	$4.25	$4.15	$4.15
Third	$2.60†	$2.75	$2.85	$2.85	$2.90
Fourth	$3.35	$3.50	$3.55	$3.65	$3.80
Fifth	$3.25	$3.50	$3.80	$3.80	$3.90

*A sudden increase in price may have several reasons, such as (1) a mistake, (2) a new, inexperienced estimator, (3) a sudden surge in costs within that particular area, (4) the company does not want this business.

†Too low cost in comparison with other vendors may be caused by one (or more) factors: (1) cheap, but poor quality workmanship, (2) new vendor, making an attempt to pay entry into a field, (3) the company has a large stock of some material it is trying to dispose of, (4) an estimate copied over and over, each time with a slight increase, but overall wrong.

Rates comparing various estimates to the original amount submitted by the particular vendor should be calculated to evaluate the degree of increase for each manufacturer (Table 15-2). Knowing such a probable rate of increase may prove useful when pricing other items from the same source: An older estimate may be used with a proper increase added to it.

The highest increase in price is 12 percent (year to year), which may still be considered a rather reasonable raise. Usually, unless something is wrong with the economy, or unless the business field is quite unique, with metal manufacturing, an increase of 6 to 10 percent on the average may be expected.

These percentages of change may allow us to estimate subsequent costs on the basis of a few old quotes. But beware, in several instances this may not be true:

- When ownership changes, companies may suddenly use completely different rates, with estimates coming out within a totally different range.
- Vendor ownership may change or a supplier may be replaced. Beware, as you may not know the new vendor's quality range.
- A mistake could be made and copied over a span of time, increasing slightly in value each year. True, the company still must perform the job for the estimated cost, but they will need to cut corners in order to fit the estimated amount.
- An estimate may be made of another estimate. Someone looked at the object and came up with the price offhand. Such costs usually don't make it, and if the production is forced upon the vendor, the quality suffers.

Percentage rates may be calculated on additional information and will certainly prove to be very useful. For example, if one vendor is always slightly ahead of the other vendor

TABLE 15-2 Percentages of the Cost History

Percentages of increase or decrease were calculated on the difference between successive years.

Vender	Jan 01	Jan 02	Jan 03	Jan 04	Jan 05
First	Base	+12	±0	+31.5	−21.5
Second	Base	+12	+1	−2.5	±0
Third	Base	+6	+4	±0	+2
Fourth	Base	+4.5	+1.5	+3	+4
Fifth	Base	+8	+8.5	±0	+2.5

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in cost, the ratio of the usual difference between these two vendors may be established, and if a quote from one of them is received, the second cost may be proportioned. Sometimes it pays, if the product to be made is difficult to produce, to know such ratios of difference and opt for a vendor who is perhaps expensive but very thorough, and is capable of delivering a high quality merchandise. In such a case, proportioned costs may often be used, since we still have the lower-pricing vendor to fall back on.

In order not to err in such an assumption, an additional cost adjustment may be appropriate. For this reason, the history of all costs over a period of time should be continuously compared to the estimator's own percentages of difference, to be able to assess a ratio of error.

If—for example—the cost was $3.35 in 2001 and $4.40 in 2003, there is a 31 percent increase in 2 years. However, if a new cost estimate arrives in 2005, pricing the job at an additional difference of 3.5 percent, this is the deviation between the assumption and the actual estimate. Therefore, an estimate based on a percentage-prorated cost variation should include an additional 3.5 percent for the protection of correctness.

Ratios between costs of various vendors may supply additional information. By assessing the difference between their quotes, we may find that one vendor is always 10 percent higher than the other, but the quality is always better, even though deliveries suffer. Or the quality may be inferior and deliveries are still worse.

Variations are endless, and each assessment should rate vendors accordingly, since only this way may the actual condition of the order be predicted. Perhaps sometimes it would be appropriate if the delivery is made slightly later, as long as the quality is there, while at other times a lower quality suffices as long as parts are delivered on time, and so on. At the end of such selective process, we may end up with but a few vendors, who would always get the job they quoted and who will deliver on time. Their products will be of acceptable quality and none of us will waste our time and resources on needless quoting.

15-2-2 Work Intensity History

It surely pays to know how much work was done for the price charged. Sometimes drilling a hole in a part may produce a whole scale of pricing of such a simple task. A good estimator will always note such differences not only by judging the price variations from vendor to vendor but by assessing the amount of work performed.

Let's say we have a part as shown in Fig. 15-1. It is a punch, into the flange of which four holes have to be drilled. Their size is quite precise; therefore, we may immediately

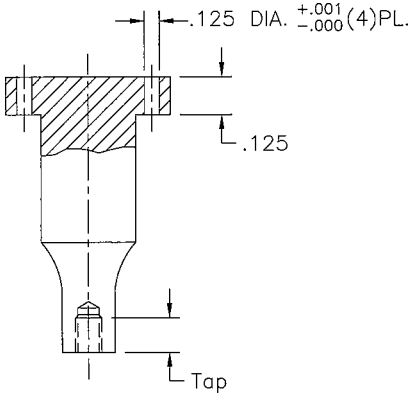

FIGURE 15-1 Workpiece.

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assume three tools with a single setup each (1—spot drill, 2—roughing drill, 3—finishing reamer). Off the other side, a tapped hole has to be added, which means that the part has to be removed from a fixture, reversed, and fixtured again. The hole has to be spotted, drilled, and tapped. This means two drilling passes, one tapping, and an additional setup cost. We may sum up the above information as follows:

2 setups	12 units of work
2 spot drills	2 units of work
2 drills	3 units of work
1 finishing tool (reamer)	2 units of work
1 tap	3 units of work

We assume that to drill a 1/8-in-thick punch flange with a 0.093-in-diameter drill may be done in a single pass. But with the 3/8-in depth of the tapped hole, the scenario may be different: We may need to drill such an opening at no less than two passes in order to accomplish a decent cut. Therefore, this hole will count as two drilling passes, as the list above indicates.

Three operational units for the tap drill are given in order to equalize its work rate with that of drills and a reamer. The tap drill will certainly run at a slower speed; therefore, its work cycle must be made proportional to the other tooling.

Assigning values to the above, we may figure that one unit of work is worth (in this case) 10 s of time, with each setup being equivalent to a minute. To assess the total cost of such a job, we simply add up all the units and multiply the number by a shop rate for the particular machine, adding a prorated overhead, or:

$$22 \text{ units} \times 10 \text{ s (each)} = 3.67 \text{ min}$$

Considering the shop rate for the particular machine to be \$45 per hour, the amount of this cost per minute will be \$0.75.

Therefore,

$$3.67 \text{ min} \times 0.75 = \$2.7525$$

The cost of drilling the holes into one punch (shown in Fig. 15-1) will be \$2.7525. This cost, however, does not include the setup time of tooling, which has to be divided into the whole order or into applicable segments of it. To position a single tool within a tool holder, along with the time to locate such a tool, will take approximately 3 to 5 min, depending on the order of a shop. We have five different tools (1—spot, 2—rough drills, 1—reamer, 1—tap), which utilize 6 tool-changing charges (Fig. 15-2).

Considering each tool change *TC* at a rate of 5 min, the total cost is

$$TC = 0.75(6\ S/U \times 5 \text{ min}) = \$22.50$$

where 0.75 = tool shop rate per minute, or \$45/60

The cost of \$22.50 applies to the total order of pieces unless this amount is separated by partial delivery requirements. Assume we need 200 pieces of these parts, which finalizes the calculation

$$200 \times \$2.7525 \text{ each} = \$550.50$$

$$TC \text{ charge, all} = \$22.50$$

$$\text{Total cost} = \$573.00$$

To get the actual cost of each drilled punch, the total amount must be divided into the number of parts, to arrive at the adjusted price, which will include the tool change charge, as

$$\$573.00{:}200 = \$2.865 = \$2.87 \text{ each}$$

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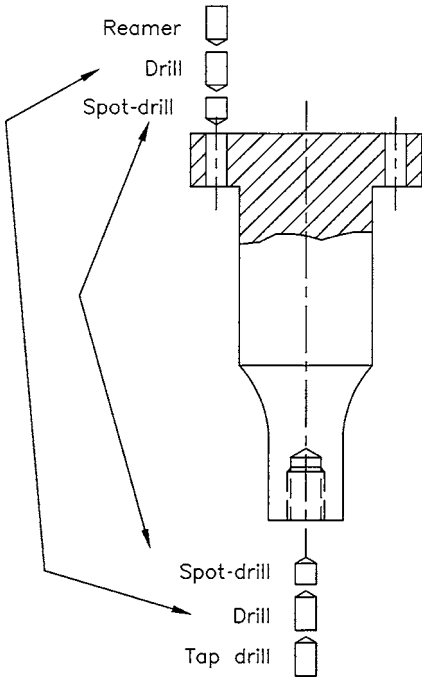

FIGURE 15-2 Work sequence.

Obviously, the more pieces produced on the same setup, the more advantageous cost-wise such an arrangement is.

Where evaluating a cost submitted by another company, all the above items must be assessed the same way. The difference between the bare cost ($2.87/piece) and their estimate is attributable to the cost of overhead and company's profit. Overhead, on the average, may run anywhere from 150 to 350 percent and even up, with dependence on the type of work, type of product, range of processes and services it covers, and many other aspects.

Companies sometimes operate on a 60 percent margin, which means that the total manufacturing cost of the product makes 40 percent of the price. Some companies, however, may operate on a 50 percent or 40 percent margin or any other fractional value of the total cost. By a careful scrutiny of their estimates, this information may be extracted and used for our own purpose.

15-2-3 Additional Costs

The above cost estimate is bare, without any expenses for inspection, overhead, company profit, and other costs and charges, whatever they may be. These naturally have to be added on in order to complete the calculation. Since these charges may vary from place to place, they are not included here.

Inspection costs are based on the accuracy of dimensions to be checked and the frequency of checking procedure (Table 15-3). Some production runs may need every 100th piece inspected, others every 25th piece, and some operations have to be inspected step by step,

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TABLE 15-3 Checking Frequency

Tolerance, in.	Ratio—1 part to
Less than 0.0005	½
0.0005–0.001	1
0.002	5
0.003	10
0.004	15
0.005	20
±0.005	25
±0.010	50
±0.031	100

Source: W. A. Nordhoff, *Machine Shop Estimating*, McGraw-Hill, New York, 1960. Reprinted with permission from The McGraw-Hill Companies.

every single part. Dimensions with greater tolerance range take less time to inspect than those with tight tolerence, because often a different set of checking instruments must be used. An approximate time comparison for checking dimensions is included in Table 15-4.

With a series of products to manufacture, usually a first-piece inspection has to be performed. This means that the first article or first few pieces are scrutinized for any discrepancies so that the rest of the run will not come out of production faulty.

On machining of the first piece, the operator must submit it to inspection and cannot continue producing other parts until the first product is approved. Such inspection may be time-consuming, or the quality control department may be jammed up with additional work. In either case, the operator must stand by and wait, unable to change the setup in the

TABLE 15-4 Time in Minutes to Check One Dimension

Instrument	Min
With rule	0.10
Outside micrometer	0.15
Inside micrometer	0.30
Depth micrometer	0.20
Dial micrometer	0.30
Outside calipers	0.05
Inside calipers	0.10
Plug gauge	0.20
Snap gauge	0.10
Surface gauge	0.20
Thread snap gauge	0.15
Thread gauge (male, female)	0.30
Thread micrometer	0.25
Vernier calipers	0.50

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machine because that would render the first-piece inspection useless. And unless another job can run on the same setup or another machine can be used to work on something else, it's just stand by and wait.

Such waiting time may add up to 25 percent of the total cost of that part. Naturally, in some instances the amount of standby time may be lower, but depending on the situation, it may also be higher.

Another set of work-influencing factors are personal adjustments, which usually run within 5 to 10 percent and perhaps even higher. This is the time an operator needs for personal survival of the workday, including trips to the lavatory, water drinking, and so on.

Personal fatigue caused by the monotony of work is another factor slowing down the production. Where the work-learning curve is raising production rate with dependence on the time spent on a job, at a certain moment it is replaced by the boredom caused by a too well known set of movements.

Additional factors enhancing the fatigue and boredom may include:

- Semiautomatic work processes, where the handling time is much lower than the actual part-producing time. These losses may amount to 5 to 10 percent, depending on the ratio of handling to the work-producing time.
- Close-tolerance work of ±0.0003 to ±0.005 in. and lathe operating cycles of 30 or fewer per hour. Such losses may run in the vicinity of 15 percent.
- Cycles, starting abruptly or fast, regardless of their total length. Extreme close-toleranced work, short cycles. Also blind hole drilling and tapping, filing, and bench work. The time loss may add up to 20 percent.
- Physically demanding work, plus deep hole drilling, high-speed milling, or operations with handling time much greater than actual machining time. Additionally, all hazardous procedures, such as sandblasting, torch cutting, and buffing. Up to 25 percent should be figured for such losses.

Some companies may include many such losses within their overhead allowance, along with the scrap rate, cost of inspection, cost of adjustments, etc. Such possibilities should be investigated prior to committing the basic cost estimate to further adjustments.

15-2-4 Machinability of Materials

Machinability of materials presents another variable in the cost estimate. Not all steels may be machined equally fast, and the amount of impairment their machinability index may cause should be some how considered in every estimate as well (Table 15-5).

The main factors influencing machinability are the hardness of the material and the amount of some of its alloying elements. Materials of hardness approximately *HB* 180 may be considered easily machinable, especially if their ductility is lower. High-speed steel tooling may use 25 percent higher cutting speeds than those generally given in charts for cutting of annealed materials. Machinability of cold-rolled material is approximately 20 percent better than that of hot-rolled stock.

The machinability of steel goes down with increase of carbon content. Lead, manganese, and sulfur improve the machinability, but greater amounts of sulfur may be detrimental to it. This applies especially to sulfur in the form of sulfides, which are found distributed throughout the material in the form of small but quite hard particles. These small pieces tend to dull the tooling, aside from the fact that sulfur enhanced the brittleness of materials.

Generally, gray iron is easily machinable but may be hard and brittle and difficult to work with if rapidly cooled during its manufacturing process. With this type of material, the surface displays worse machinability than the core.

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TABLE 15-5 Materials Grouped by Machinability*

Group	Group name	Materials			Cutting speed, ft/min.†
I	Magnesium	Magnesium alloys: Sand castings Permanent-mold castings Extruded bars, rods, and shapes Die castings Forgings			2000
II	Aluminum	Aluminum alloys: Sand castings Permanent-mold castings Extruded bars, rods, and shapes Die castings Forgings Phenolic			1000
III	Brass	Copper alloys: Free-machining yellow brass Phosphor bronze (free-cutting) Bearing brass Hardware bronze Red bronze (80%) Commercial bronze Copper (leaded) Brass forgings High-strength commercial bronze Naval brass (leaded) Government babbitt Plastics Formica Micarta Zinc alloys Kirksite			250
IV	Screw stock	Carbon steels: B-1006 B-1010 C-1005 C-1006 C-1008 C-1010 C-1012 C-1013 C-1015 C-1016 C-1017 C-1018 C-1019 C-1020 C-1021 C-1022 C-1023 C-1090 C-1095	Free-cutting steels: C-1106 C-1108 C-1109 C-1110 C-1111 B-1111 B-1112 B-1113 C-1113 C-1114 C-1115 C-1116 C-1117 C-1118 C-1119 C-1120	Miscellaneous: Cast iron (soft) Malleable iron (soft) Leaded phosphor bronze 5% Yellow brass Muntz metal Red brass 85% Red brass 80% Naval brass Tobin bronze Manganese bronze Hard rubber Bakelite	125

(*Continued*)

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TABLE 15-5 Materials Grouped by Machinability* (*Continued*)

Group	Group name	Materials			Cutting speed, ft/min.†
V	Mild steels	Carbon steels:	Free-cutting steels:	Molybdenum steels:	75
		C-1024	C-1125	4130(A)	
		C-1025	C-1126	4140(A)	
		C-1026	C-1132	4150(A)	
		C-1027	C-1137	4340(A)	
		C-1029	C-1138	4615(A)	
		C-1030	C-1140	4615(CR)	
		C-1033	C-1141	4620(A)	
		C-1034	C-1146	4620(CR)	
		C-1035	C-1151	4640(A)	
		C-1036	Manganese steels:	4815(A)	
		C-1038		Chromium-vanadium steels:	
		C-1039	1315	6120(A)	
		C-1040	1320	6130(A)	
		C-1041	1321	6135(A)	
		C-1042	1330	6140(A)	
		C-1043	1335	6150(A)	
		C-1045	1340	Miscellaneous:	
		C-1046	Nickel steels:	Cast iron (medium)	
		C-1049		Malleable iron (medium)	
		C-1050	2135(CR)‡	Meehanite (soft)	
		C-1051	2320(A)§	Copper (electrolitic)	
		C-1052	2340(A)	Bronze (commercial 90%)	
		C-1054	2512	Phosphor bronze	
		C-1055	2515	Aluminum bronze	
		C-1057	2517	Spinning brass	
		C-1060	Nickel-chromium steels:	Copper tubes	
		C-1061		Copper wire	
		C-1062			
		C-1064	3120(CR)		
		C-1065	3130(A)		
		C-1066	3140(A)		
		C-1069	3220(A)		
		C-1070	3230(A)		
		C-1071	3312(A)		
		C-1074			
		C-1075			
		C-1078			
		C-1080			
		C-1084			
		C-1085			

(*Continued*)

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TABLE 15-5 Materials Grouped by Machinability* (*Continued*)

Group	Group name	Materials					Cutting speed, ft/min.†
VI	Medium steels	Nickel steels: 2317 2320 2330 2335 2340 2345 2350 2515 Nickel-chromium steels: 3115 3120 3130 3135 3140 3141 3145 3150 3220(CR) 3230 3240 3240(CR) 3250 E3310 3312 E3316 3340 3450	Molybdenum steels: 4017 4023 4024 4027 4028 4032 4037 4042 4047 4053 4063 4068 4130 E4132 4135 4137 E4137 4140 4145 4147 4150 4317 4320 E4337 4340 E4340 4608 E4617 4620 X4620 E4620 4621 4640 E4640 4812 4815 4817 4820	Chromium steels: 5045 5046 5120 5130 5132 5135 5140 5145 5147 5150 5152 E50100 E51100 E52100 Chromium-vanadium steels: 6120 6130 6135 6140 6145 6150 6152	Nickel-Chromium steels: 8615 8617 8620 8622 8625 8627 8630 8632 8635 8637 8640 8641 8642 8645 8647 8650 8653 8655 8660 8719 8720 8735 8740 8742 8743 8747 8750 Miscellaneous: Cast iron (hard) Malleable iron (hard) Meehanite (medium) Cast steel (soft) Beryllium copper Drill rod Titanium: RC-70	Stainless steels: 303 403 405 410 412 414 416 430 430F 440F	50

(*Continued*)

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TABLE 15-5 Materials Grouped by Machinability* (*Continued*)

Group	Group name	Materials			Cutting speed, ft/min.†
VII	Hard steel	Silicon-manganese steels: 9255 9260 9261 9262 E9310 E9315 E9317 9437 9440 9442 9445 9747 9763 9840 9845 9850	Stainless steels: 301 302 304 308 309 310 316 317 321 329 330 347 431 440 442 443 446 501 502	Miscellaneous: 18-8 stainless (alloys 302, 304) K-monel Inconel Heat-treated steels (160,000–180,000 lb/in^2) Meehanite (hard) Cast steel (medium) Beryllium copper (heat-treated) Titanium: RC-130B TI-150A Timken Konal	35
VIII	High-temperature alloys	Stainless steels: 420 420F 440A 440B 440C		Miscellaneous: Cast iron (chilled) Heat-treated steels (180,000–200,000 lb/in^2) Cast steel (hard) Titanium: MST Discalloy Hastalloy B Hastalloy C	25

*Based upon high-speed-steel single-point turning tools.
†Cutting speeds are based on depth of cuts of 0.125, feed rates of 0.020 in/rev., and a tool life of 2.0 h.
‡CR = cold-rolled or cold-drawn.
§A = annealed.
Source: W. A. Nordhoff, *Machine Shop Estimating*, McGraw-Hill, New York, 1960. Reprinted with permission from The McGraw-Hill Companies.

Machinability of materials is further influenced by the type of tooling used and its quality. Various tooling materials work at different rates of metal removal, with variation in the obtained surface finish as well. Some numerical differences between tooling materials are given in Table 15-6. The multiplying factor in this table clearly indicates the difference between tooling material qualities, and it should be applied to the given tool rates as listed in various charts.

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TABLE 15-6 Cutting Tool Material Multiplying Factor

Tool material	Multiplying factor
Carbon tool steel	0.50
High-speed tool steel	1.00
Super-high-speed tool steel (Stellite, etc.)	1.50
Carbide (Carboloy, etc.)	3.50
Aluminum oxide and ceramics	7.00

Machinability of material is also influenced by the type of cutting tool used. Single-point tooling has the best stock-removing capacity, while drills and reamers are quite slow at cutting, using approximately half of the single-point tooling's cutting speeds. An additional factor applicable to all cutting speed charts compares different machining operations by showing percentage values of applicable speed, as shown in Table 15-7. This multiplying factor should be used with Table 15-5 to fine-tune the given values for the appropriate machining operation.

However, even with all these adjustments there may be situations when we cannot evaluate the actual process of producing a given part, as sometimes the surface finish of the cut or some other precision-related demands may lower the speed and feed of the tooling still further, throwing off all the expectations of the estimator.

The depth of the cut is another factor influencing the machinability of materials. Block 1/4 in. thick will certainly be drilled differently than the same opening in 1-in block. Going through such a thickness, the tool cannot accomplish the task at a single pass. It must come down, return to dispose of chips, and come down again, sometimes repeating this procedure several times.

Spindle speeds and cutting speeds are given by a ratio:

$$C = \frac{\pi DN}{12} \qquad \text{or} \qquad N = \frac{12C}{\pi D}$$

where C = cutting speed, ft/min
D = diameter of work cutter, in (Fig. 15-3)
N = number of revolutions of spindle, rev/min

Setup, fixturing, and support of the machined part are of extreme importance for its machinability. If the part is loose, machining feeds and speeds will be impaired by the amount of its chatter. Naturally, the size of the cutting tool is of importance as well, since small drills (and first-use drills in general) cannot operate at such cutting parameters as heavy, sturdy, large-diameter tools. For more on cutting of materials, see Sec. 4-4 "Machining of Blocks."

Generally accepted working feeds for carbide single-point tools for turning, boring, and facing are presented in Table 15-8.

Feeds and speeds of cutting tools influence not only the condition of a cut, such as its surface finish, straightness, roundness, and concentricity, but also the tooling itself, causing it to succumb to wear and tear under unreasonable operating parameters. (See Figs. 15-4 through 15-6.) Tool life, if shortened unnecessarily, drives the cost of production high not only because of its breakage but also because of the greater than usual

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TABLE 15-7 Cutting Tool Machining Factors

Operation				Factor	Max. spindle speeds
Turning				1.00	No limit
Boring				0.75	No limit
Broaching				0.25	
Counterboring:					
Solid counterbores (piloted)				0.50	No limit
Spot facer (piloted				0.50	No limit
Inverted spot facer (piloted)				0.50	No limit
Back spot facer (piloted)				0.50	No limit
Center reaming (solid center reamer) (for internal chamber or countersink)				0.50	No limit
Countersinking (combination drill and countersink)				0.50	No limit
Cutting off				1.00	No limit
Drilling				0.50	No limit
Start drilling				0.75	No limit
Center drilling				0.75	No limit
Forming				1.00	No limit
Gear-shaping cutters				0.75	200–450 strokes per min
Gear-generating tools				0.75	No limit
Gear-shaving cutters				1.50	No limit
Hobs				0.50	No limit
Hollow milling				1.00	No limit
Knurling:					
Aluminum Magnesium Brass (500 ft/min)	Screw stock Steel, mild (150 ft/min)	Steel, medium Steel, hard (100 ft/min)			
Milling (general)				1.00	No limit
Metal-slitting saws				0.50	No limit
Pointing and facing tools				1.00	No limit
Reaming:					
Ordinary reaming; reaming for size				0.75	No limit
Reaming for high degree of finish				0.25	No limit
Recessing tools:					
End cut				1.00	No limit
Inside cut				0.75	No limit
Threading (without lead screw)					
Dies	Aluminum Magnesium Brass	Screw stock, steel mild	Steel, medium, steel hard		
(Self-opening)	30 ft/min	20 ft/min	10 ft/min		250
Dies (button)	30 ft/min	20 ft/min	10 ft/min		250
Taps (solid)	30 ft/min	20 ft/min	10 ft/min		250
Threading (with leadscrew)					
Dies					
(Self-opening)	30 ft/min	20 ft/min	10 ft/min		No limit
Dies (button)	30 ft/min	20 ft/min	10 ft/min		No limit
Taps (solid)	30 ft/min	20 ft/min	10 ft/min		No limit
Threading (single-point high-speed-steel tool)				0.75	150
Thread milling				1.50	No limit
Thread rolling				1.00	No limit

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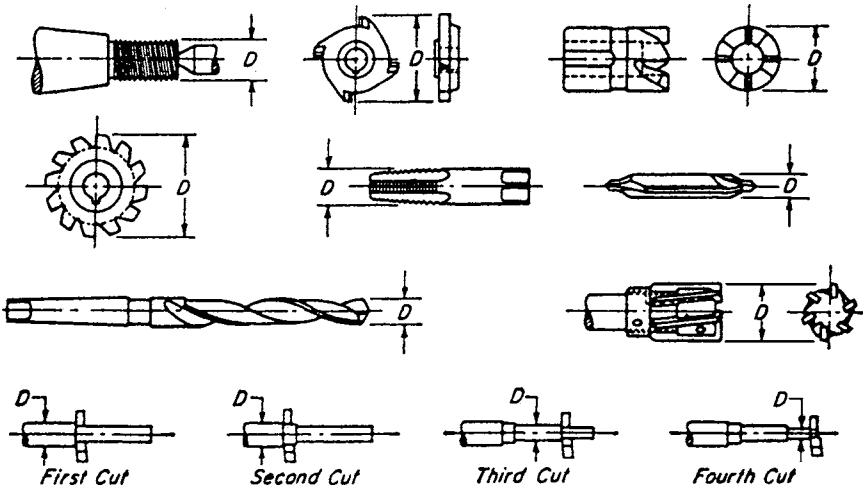

FIGURE 15-3 Examples showing the value of D in the formula $C = \pi DN/12$ (in). (*From W. A. Nordhoff,* "Machine Shop Estimating," *McGraw-Hill, New York, 1960.*)

TABLE 15-8 Feeds for Single-Point Carbide Tools

	Feeds	
Materials	Rough	Finish
Carbon steels (10xx)	0.015–0.020	
Free-machining (11xx)	0.010–0.020	
Manganese (13xx)	0.015–0.025	
Nickel steels (23xx) (25xx)	0.012–0.022	
Nickel-chrome (31xx) (33xx)	0.010–0.020	
Molybdenum (40xx) (41xx)	0.010–0.020	
(46xx)	0.015–0.030	
Chromium (50xx)	0.010–0.020	
(86xx)	0.010–0.020	
Stainless steels	0.005–0.015	0.003–0.007
Titanium	0.008–0.015	
Heat-resistant alloys	0.015 min	
Cast iron	0.015–0.025	0.010–0.015
Malleable iron	0.015–0.020	0.010–0.015
Nickel alloys (monel, K-monel)	0.010–0.020	0.003–0.010
Copper alloys:		
Free-cutting	0.007–0.020	0.005–0.009
Average machinability	0.007–0.018	0.003–0.008
Difficult to machine	0.003–0.015	0.003–0.005
Aluminum alloys	0.007–0.012	0.003–0.008
Magnesium alloys	0.010–0.040	0.005–0.010
Plastics	0.003–0.008	

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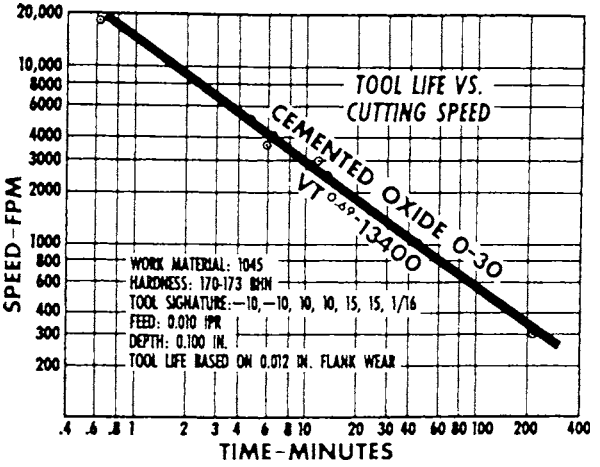

FIGURE 15-4 Cemented oxide tools show a straight tool-life over a broad range of speeds. (*From R. G. Brierley and H. J. Siekmann*, "Machining Principles and Cost Control," *McGraw-Hill, New York, 1964. Reprinted with permission.*)

setup charges, tool-installation charges, number of rejects before the dulling or breakage is registered, or outright a number of ruined pieces and cost of their material.

A comparison of tool life is given in Table 15-9 in an attempt to relate the actual situation to that written on paper or, worse, estimated. The amount of tool life is given in arbitrary units.

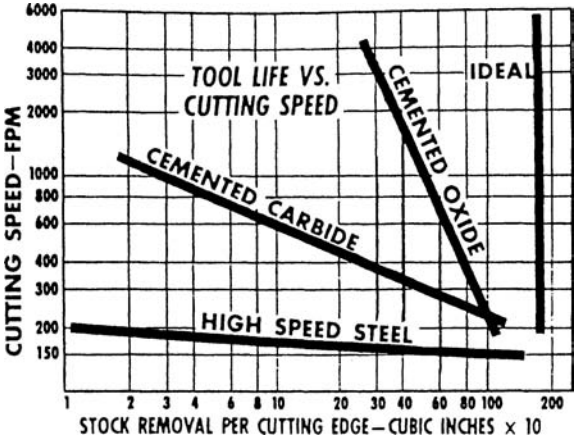

FIGURE 15-5 Modern cutting-tool materials approach the ideal concept of a constant amount of stock removal per cutting edge at any speed. (*From R. G. Brierley and H. J. Siekmann,* "Machining Principles and Cost Control," *McGraw-Hill, New York, 1964. Reprinted with permission.*)

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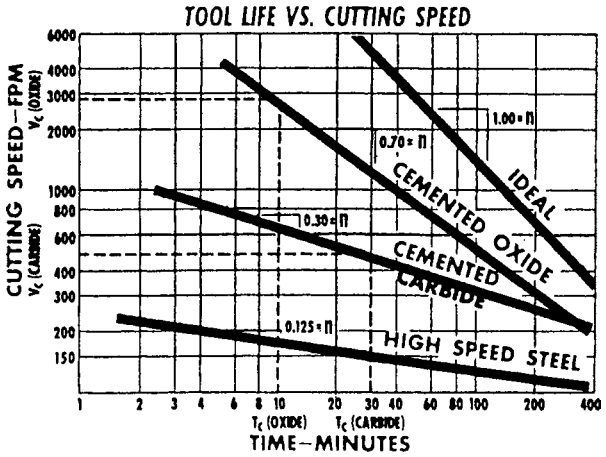

FIGURE 15-6 Different classes of tool materials have distinctively different tool-life line slopes. (*From R. G. Brierley and H. J. Siekmann*, "Machining Principles and Cost Control," *McGraw-Hill, New York, 1964. Reprinted with permission.*)

TABLE 15-9 Normal Tool Life, High-Speed Tool Steel

Type of cutting tool	Aluminum brass	Mild steel	Hard steel
Drills:			
Under 1/16 in. diameter	30.0	20.0	10.0
1/16 – 1/2 in.	45.0	30.0	15.0
1/2 in. and over	60.0	45.0	30.0
Taps:			
Under 1/16 in.	60.0	40.0	20.0
1/16 – 1/2 in.	90.0	60.0	30.0
1/2 in. and over	120.0	90.0	60.0
Milling cutters:			
Metal-slitting saws End mills under 1 in. diameter Slotting cutters 3/32 in. and under Woodruff key seaters Slotting cutters over 3/32 in.	60.0	45.0	30.0
Plain-milling cutters End mills over 1 in. diameter Angle-milling cutters	120.0	90.0	60.0
Hobs:			
Gear Spline Serration Thread	360.0	270.0	180.0
Turning and boring tools Shaper tool Thread chasers	120.0	90.0	60.0

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15-2-5 Cost of Material

The cost of material was not included in the calculation in Sec. 15-2-2 "Work Intensity History," since the basic part, the punch, was being supplied by the vendor. However, where the material has to be obtained, its pricing must be included in the cost.

Material cost should be handled in the same fashion as any other cost. Prices of different suppliers may be prorated, to assess the percentage difference among various sources. In order to calculate a whole range of steels from a single material estimate, the financial difference between materials has to be assessed as well. After all, alloying elements such as nickel, chromium, vanadium, titanium, and others increase the cost of material in approximately the same way. Also their pricing is rather consistent, unless a disaster strikes the place on earth where such and such an element is mined or otherwise obtained.

For example, should we consider SAE No. 1300 alloy to be a basis for the new comparison chart, we may use such a base for development of other materials' prices, as shown in Table 15-10.

Cold-rolled stock is usually higher in cost than hot-rolled material. The difference may be in the neighborhood of 20 percent, depending on the actual mill process. It is worthwhile to question the sales personnel of a particular mill and find out exactly what's involved in each manufacturing method.

The cost ratios presented in Table 15-10 should be considered arbitrary, as every mill may have a slightly different set of prices, which will vary with dependence on sources of ingredients, the manufactured amounts, the demand for the particular material, and many additional factors tied to its production and sale. The percentages and monetary values given throughout this chapter are merely guidelines for a person who is eager to do not only die design, die manufacturing, and die-related production, but the costing as well. These numbers have to be adjusted or fine-tuned for each applicant's scenario and sources.

Prorating of materials according to their ingredients and manufacturing processes may serve as yet another set of guidelines for all subsequent quoting work. Alloying elements and their quantity should be of special interest, as inclusion of some will considerably influence the final cost. We may observe that wherever a higher percentage of nickel is added, the cost of such steel jumps up. The same applies to molybdenum.

Nickel is obtained mostly from nickeliferous and cupriferous pyrrhotite, by smelting in blast furnaces. Molybdenum is a metallic element of the chromium group, occurring in a combination of molybdenite, wulfenite, and molybdite. Molybdenum is of American origin (Arizona, Montana, Nevada, Utah), but nickel is produced by Myanmar (formerly Burma), China, Albania, Botswana, Indonesia, Zimbabwe, New Caledonia, and similar

TABLE 15-10 Comparison of Cost of Steel Materials

Material	Alloying elements	Percentage of price
1300	0.28–0.33 C, 1.6–1.9 Mn	100
2517	0.15–0.2 C, 0.45–0.6 Mn, 4.75–5.25 Ni	189
3135	0.33–0.38 C, 0.6–0.8 Mn, 1.1–1.4 Ni, 0.55–0.75 Cr	122
4130	0.28–0.33 C, 0.4–0.6 Mn, 0.8–1.1 Cr, 0.15–0.25 Mo	118
4615	0.13–0.18 C, 0.45–0.65 Mn, 1.65–2.00 Ni, 0.2–0.3 Mo	140
5120	0.17–0.22 C, 0.70–0.90 Mn, 0.70–0.90 Cr	110
6120	0.17–0.22 C, 0.70–0.90 Mn, 0.70–0.90 Cr	140
9260	0.55–0.65 C, 0.70–1.00 Mn	111

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TABLE 15-11 Stock Allowances for Rough Cutting, to Be Removed in Machining

Material type and shape	Amount to be added for machining (per cut), in.
Hot-rolled stock, general	0.125–0.375
Cold-rolled stock, general	0.015–0.187
Cold-rolled flat stock, thickness	0.015–0.187
Cold-rolled flat stock, width	0.015–0.093
Round stock, length	0.062–0.187
Any stock used for chucking	1.25–2.00

countries, aside from some Canadian and Norway production. Naturally, following the world news should prove helpful to the eager estimator.

In the evaluation of any particular material quantity needed for production, the so-called scrap rate should not be overlooked. Scrap rate is the amount of ruined and otherwise destroyed material, which is usually used for testing, for trial runs, or that which is accidentally crushed, ruined, and so on. Scrap rate may also contain material supplied in larger than necessary sizes, or where a certain percentage must be added to a rough cut, to be later removed by the machining process. Various types of materials and their shapes may use the stock-removing allowances shown in Table 15-11.

Scrap rate may run in percentages of 5 percent and up, with dependence on the type of production, sensitivity of handled material, training of the personnel, and numerous other aspects.

15-2-6 Evaluation

In spite of all guidelines and tables presented here, and elsewhere, the estimator's job is never an easy one. First of all, every evaluation is based solely on assumptions. Existing time studies don't help, because they always pertain to jobs already done, in which case they were studied after a number of successive repeats, when the operator had already acquired considerable skill doing the same job over and over. The estimator cannot depend on such time and monetary values. Unknown obstacles the new production may bring about and little surprises that may come out of hiding in the woodwork once the job hits the shop floor remain unpredictable.

Naturally, this applies to production runs of multitudes of pieces. With an individual work, or research and development projects, which die design and die building often are, every new assignment may be completely different from the previous one. An approach that worked well once may be useless the second time around, and the speed of a work process is determined more by a lack of difficulties encountered than by the preventive treatment of their expected appearance.

Further, all textbook types of calculations and evaluations don't work the same way for each particular machine shop. In some places the order of the shop floor may be exemplary, with properly marked tools placed within well accessible cabinets. Other places may have chaos instead of an organizational strategy, with toolmakers borrowing the tools from each other, with many tool sizes missing, or with chipped or dull tools that nobody sharpens. Factors such as these may never be included in the form of any ratios or as tabulated. These influences are unaccountable, as they change with the day, with the job, with the number of people who decided to appear for work.

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DIE COST ESTIMATING

Some estimators like to work by the book, and they cannot be blamed, because it is much easier. However, how much will these nicely added up costs of all necessary operations fare when compared to actual shop floor values? Does the company really support the formulas they're using? Is the leadership willing and able to provide a workplace where things can be done such a way? And do the workers appreciate such efforts? Are they really conscientiously striving to produce their best? Or is it all just one large utopia depicting how we all would like to work and operate?

If the latter is true, a company is heading for ruin, because estimates, no matter how much estimated they are, must be in congruence with actual numbers. How else can a firm make a profit if the real time to make an item is twice its estimated value?

For these obvious reasons, sometimes it pays to further evaluate each job visually as well, imagining operations as they are performed, trying to foresee obstacles and assess parameters and guidelines. If the formula says it should be done in 5 minutes—can it really be done at such a time? Well, perhaps Mike would do it if he gets the job, but Tony will never fit into such numbers. Yet Tony delivers high-quality workmanship and Mike tends to be sloppy at times. Comparisons such as these are additional factors influencing the work flow and its quality.

When it comes to such wide-ranging variables, the work history and history of the work intensity may prove invaluable for every estimator, designer, engineer, industrial engineer, and everybody else up to the general manager of the plant. These records, when continuously updated and compared with real outcomes of previously estimated jobs, will give the historically correct information about all work already done. In such a case it will be much easier to estimate a job which looks like something else, something already known and familiar. In this way the history may guide and focus the estimating process, perfecting the outcome up to a total flawlessness.

Needless to add, all records should be written, preferably stored in a computer. To depend on memories of those who were then involved in such and such a process is a highly risky and inaccurate manufacturing method. It may suffer from impairment caused by an occasional memory loss, or become inappropriately influenced by seasonal activities such as vacations, or be severely crippled by the particular key person not showing up for work or retiring.

Where the actual records are found different from the basic estimate, a correction factor should immediately be established and used in subsequent quotations. Such a correction factor may be calculated by using these formulas:

$$CF = 100\frac{A}{H} \qquad \text{or} \qquad CF = 100\frac{A}{E}$$

where CF = correction factor, percentage
A = actual data
H = historic data
E = estimated data

Some may argue that such a procedure is very time-consuming and costly, which may or may not be true. It all depends on the way such a method is set up, and it all depends on the equipment available for the purpose. Where the estimator may use a computer, which is now mostly the case, any basic spreadsheet program such as Lotus 1-2-3 may do the job. If properly formatted, the software will calculate the appropriate percentages, ratios, additions or subtractions, and similar mathematical tasks by itself, as soon as the basic numerical input is typed in.

Sometimes such a procedure is much cheaper than sending out desperate faxes begging for a quote, and wasting precious time and stomach lining over the cost that is just not coming in.

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More advanced computerized help may be obtained by employing any programming language, such as C-programming or C++. Such assistance is immeasurable, especially where whole charts of information are created, evaluating an array of outcomes from a limited numerical input. By giving the basic solid information to the computer, the compiler spits out a complex charted answer in a matter of seconds, provided, of course, that the initial set of directing commands is correct.

15-2-6-1 Quality Control Input. The quality control department should have a definite say in the estimating procedure, even though not many estimators realize it. We should not forget that all the incoming parts, materials, assemblies, subassemblies, and other objects to be included in the manufacturing process first land in the quality control department. There they are checked out, compared to drawings or specs, and on the basis of their compliance are either released into production or rejected.

An experienced quality control inspector knows each particular vendor's strength and weakness, whom to give a deep-hole drilling job, and who will mess it up. The inspector can pinpoint the shop capable of producing high-precision parts and avoid outfits that just slap things together and hope for the best. Quality control people also know which company is responsive and which company's representative is rude or uncooperative or just never there.

An input of these people should be emphasized, as their experience with various suppliers may be worth a lot, if not exactly in monetary terms, then certainly in measures of avoidance of problems.

15-2-6-2 The Lowest-Cost Syndrome. Some manufacturers tend to think that the vendor who submits the lowest cost is the best candidate for the job. This, however, may not always be true. Some vendors are low in cost and high in quality of their output, and other vendors are low in cost and still lower in quality. There can be jobs which two different vendors may accomplish at a price difference of hundreds of dollars. But there is a chance that thousands may be spent on bringing the produced objects within the drawing's requirements.

A manufacturer who goes to faraway countries to produce dies may save some money on such expensive tooling, but in the end, may be lucky to show a profit. After all tariffs, duties, and taxes, plus shipping costs and currency-converting fees are paid, the expected difference in price may easily disappear. The die itself may be another disappointment, for the faraway shop knows well that the overseas customer will not be returning it for repair, and some shops may even count on it. They may use inferior materials or inferior manufacturing methods, knowing that these are extremely difficult to assess and to prove. The life of such tooling may be impaired just there, at the beginning. Materials may chip off, peel off, become fractured, rusty, and who knows what, and the die that was to produce parts for many years to come may not survive two winters.

For example, in plastic injection molds' manufacture, some faraway masterminds use epoxy to "repair" cracked or faulty steel blocks so that visually the surface arrives perfect. At any rate, not much is to be seen on an assembled mold, and to take it apart is too costly and time-consuming. Well, the epoxy soon melts away, when exposed to a hot plastic material, and suddenly products emerge with craters, gaps, and valleys and all kinds of distortions, and nobody's the wiser as to where they came from.

Therefore, it may perhaps be advisable to keep a local vendor who produces parts of a good quality, even though the prices are not always what we may want them to be. Maybe the vendor's workload is prohibitive. However, it pays to investigate these possibilities and to work with such a source on an improvement. After all, a really good vendor will meet the other party halfway, provided an honest effort is produced.

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15-3 DIE BUILDING ESTIMATES

Included below are some personal observations which may be used as guidelines in die building and die design estimating. However, some adjustments for the particular application may be required, since not all people work the same way and therefore not all work is ever produced at the same speed.

We may begin with an assumption that every article produced in a die will have some alterations done to its outer shape as well as to its inner surface area. Some parts are pierced, some are formed, and others are drawn. On the average, to produce a single punch and corresponding die button and stripper guide for a piercing station always takes a certain number of hours, with dependence on the size of tooling. According to my experience, every linear distance of 10 mm, or 0.394 in. (roughly 0.4 in.), as produced by a single continuous cut, takes the average of some 2 h for a set of tooling, described previously. The cut may be straight or curved, as long as it is continuous. With round tooling, its circumference should be calculated to obtain its linear distance. With square or rectangular cuts, each side of the square or rectangle will count as a separate cut.

On the basis of such a rough assessment, time values for different sizes of tooling may be calculated as shown in Table 15-12. Here the time intervals in hours are given with respect to various sizes of the punch and with consideration of quantities of the same tooling to be produced. A time interval to machine a 0.375-in-diameter punch and die and guide bushing is figured as follows:

$$\text{Circumference} = \pi D = \pi(0.375 \text{ in.}) = 1.178 \text{ in.}$$

$$1.178 \text{ in.} \div 0.394 \text{ in.} = 3$$

$$3 \times 2 \text{ h} = 6 \text{ h}$$

We need a total of 6 h to produce this size of tooling; with two punches of the same size it will be 12 h; three tooling sets will be 18 h, and so on.

To machine punch plate, die block, stationary stripper, and two backup plates for the above tooling, the values are given in the chart with dependence on sizes as well. The basic amount of time is 20 h for the $^1/_4$-in-diameter punch. This interval increases 1 h with every $^1/_8$-in. enlargement of the punch diameter size. A set of plates for a 0.5-in-diameter station will take 23 h, which consists of 20 basic hours plus 1 h for each $^1/_8$-in. increase in diametral size.

With multiple tooling of the same shape and size, each additional tool within the same set of blocks not only will increase their proportions but will demand more machining as well. Such an increase usually amounts to +5 h for each additional tool set.

From Table 15-12, to build a die consisting of three 0.5-in-diameter punches will amount to

$$3 \times 8 \text{ h} = 24 \text{ h to machine punches, dies, and stripper guides}$$

$$23 \text{ h} + (2 \times 5 \text{ h}) = 33 \text{ h to make all necessary plates}$$

The total will come to 57 h.

Another example: A die with five 1-in-diameter tools is calculated similarly:

$$5 \times 16 \text{ h} = 80 \text{ h for punches, dies, stripper guides}$$

$$27 \text{ h} + (4 \times 5 \text{ h}) = 47 \text{ h for all plates}$$

The total time to make such die: 127 h.

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TABLE 15-12 Die-Building Cost Estimate

Hole diameter, in.	Linear dimensions or circumference, in.	To build punch and die and guide, h	Punch plate, die block, backup plates (hrs.) for a number of tools below					
			1st	2nd	3rd	4th	5th	6th
0.125	0.393	1.50(2) = 3	+20	+7.5	+7.5	+7.5	+7.5	+7.5
0.25	0.785	1.25(4) = 5	+21	+6.25	+6.25	+6.25	+6.25	+6.25
0.375	1.178	6	+22	+5	+5	+5	+5	+5
0.5	1.571	8	+23	+5	+5	+5	+5	+5
0.625	1.963	10	+24	+5	+5	+5	+5	+5
0.75	2.356	12	+25	+5	+5	+5	+5	+5
0.875	2.75	14	+26	+5	+5	+5	+5	+5
1	3.142	16	+27	+5	+5	+5	+5	+5
1.125	3.534	18	+28	+5	+5	+5	+5	+5
1.25	3.927	20	+29	+5	+5	+5	+5	+5
1.375	4.32	22	+30	+5	+5	+5	+5	+5
1.5	4.712	24	+31	+5	+5	+5	+5	+5
1.625	5.105	26	+32	+5	+5	+5	+5	+5
1.75	5.498	28	+33	+5	+5	+5	+5	+5
1.875	5.89	30	+34	+5	+5	+5	+5	+5
2	6.283	32	+35	+5	+5	+5	+5	+5

Small fragile punches are more difficult to handle, which impairs their machining time. For that reason their time values were increased accordingly, with 150 percent increase across the board for 0.125-in-diameter tool and plates set and 125 percent increase for 0.250-in-diameter tooling.

These guidelines need not be restricted to cutting tools. Actually, all punches and dies may be calculated using the same approach, with few exceptions, listed in Table 15-13.

The cost of material and the cost of any additional expenses such as heat treatment, cost of the die shoe, springs, mounting hardware, switches, cams, and all other single parts or their subassemblies must be added to the above assessment. Also not included is the cost of any special alterations of the blocks, such as nests, lift pins, and openings for ejection devices.

TABLE 15-13 Time Values for Building of Various Die Elements

Tooling to be produced	Time needed
Forming, shaving	100–120% of HPS*
Drawing	120–150% of HPS*
Guiding inserts	110–120% of HPS*
Embossing, extruding, swaging	HPS*
Strip stop, manual and automatic	Each: 5–10 h
Spring stripper	Add: 15–40 h
Knock-outs, nests, grip stripper	Each: 15–25 h
Horn, cam, side-acting tool	30–60 h
Pinch trim, curling tool	150–200% of HPS*

*HPS = hours per size, as in Table 15-12.

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But—since not every toolroom produces the tooling at the same rate as shown above, a good amount of personal observation and comparison of the above values to the actual situation should be attempted first. A subsequent modification or fine tuning of this data should follow if necessary.

15-4 DESIGN AND DEVELOPMENT COSTS

The cost of research, design, and development is often impossible to estimate. For that reason many research activities are government-subsidized, either in the form of straightforward allocation of funds to universities and colleges or as grants and other funding for a variety of privately conducted research. Such a solution is outright necessary, because as much as research and development are very much needed, they are almost equally unprofitable.

Yet, every manufacturer and every producer must conduct some sort of research and new product development, or his production standards will lag behind until finally run over by the competition. For today's industry, the design of new parts, products, or systems, and their development is an absolute must; it is a matter of survival.

Various companies comply with these demands differently. Some charge the cost of research and development (further R&D) toward their overhead, embedding it within the piece price. Others keep these expenditures separately, hoping that the prices of their products, and quantities ordered, will allow them to fit—miracle provided—their R&D activities within their range, along with marketing and advertising costs.

Design and R&D is an ongoing process, lasting a whole year, and a year after a year. Designers and engineers should always be on the lookout for possible improvements and innovations, and the company's leadership should always be patient enough to lend them an ear and sincerely evaluate their proposals and ideas. Because anyone who stands still and does not progress is actually moving backward. All the others will precede him soon, no matter how slowly they move.

Perhaps the best way to account for the design and R&D, if not proportioning its cost within the piece price, is to charge a flat rate. A simple die design will be a flat rate of—let's say—three thousand; a more complex die, twice the amount; a superdifficult die, a multiple of the basic flat rate.

The development itself is a slightly different story. Here we have more people involved, which brings an equal number of ideas, which are continuously evaluated, discussed, and evaluated and discussed again. Perhaps it would be advisable to use a rule of thumb and make two assessments of a time interval needed to come up with a solution to a given problem. One assessment takes a view of an optimist who sees the world through rosy glasses and considers a rare instance where everything works fine the first time. Then take a view of the pessimist and imagine all obstacles lurking in the background and waiting for an appropriate, or rather for the most inappropriate moment to strike.

These two ranges should give a nice overview of the situation, with the mean between the two extremes, or any other angle of preference, serving as the basis for an estimate. However, we should never forget that where two solutions to a given problem are present, the worst of them usually occurs. A view of a realistic optimist will then be to take the worst situation for valid and be pleasantly surprised if it turns out slightly better.

A problem of the cost of new development should be assessed on the basis of workhours. How many hours are needed to produce a punch and die assembly is fairly well known. If the punch and die is complex and needs some grooming in between, the number of hours spent on such job should be expected to rise in accordance with its complicity. The total number of estimated hours should be multiplied by 3 to give a range of the time span for the development of an unknown product.

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The reason behind multiplying the number of hours by 3 is as follows: one-third will be worker(s) salary, one-third will be overhead, and one-third will go against the company's profits. If one of the thirds falls short, the existence of the other two may compensate. If one of the thirds soars, it may provide some cushioning for the next time.

Another approach to the design and development evaluation is to charge a percentage of the actual die cost. For example, if building a die that is to blank and draw the part, 25 to 45 percent of the hours needed to build the drawing station alone should go against the design and development. With a blanking and forming die, the forming station will be used in such an assumption. As a rule, always the most difficult station to be produced should serve as the basis for design and development cost assessment.

Naturally values may change from company to company. It would be worthwhile to design several methods of evaluation, use them consistently, and compare results with the actual hours spent on the job.

Considering the basic die design, a simple and straightforward die, consisting of 3 to 6 stations (some may be empty) may take approximately 10 to 12 h to come up with the strip layout, as positioned on the die block. This includes all calculations, economical evaluation, and a rough blank calculation. Another 15 to 26 h will be needed to produce detail drawings, write bills of material, and do the necessary paperwork.

With a more complex die, the initial strip layout may well take 20 to 28 h, with an additional 20 to 30 h for details and paperwork.

However, this estimate may be considered valid only where no complications are involved, where all punches and dies are fairly simple, with no tryout runs needed, and where we are not dealing with any new or unpredictable materials or unknown processes.

15-5 ESTIMATE FORMAT AND TERMINOLOGY

Every submitted estimate must reflect not only the price ranges for the services rendered but also other terms of the production and its delivery, the time span needed to produce the job, where to deliver, who will pay for what and when, the number of pieces delivered, and their packaging. Otherwise such demand may be summed up as:

who-does-what-for-whom

how-why-where-when-at what price

under which conditions and restrictions

provided payment is made, when and how and in which currency

The requirements considering all the above factors may be numerous and if not properly evaluated for their full impact, may greatly impair the meaning of the estimate, with subsequent injury to the actual production of the merchandise and financial standing of the firm. Beware of conditions not specified in the estimate—they may be implied, which does not always work in your favor.

15-5-1 Delivery Timing

The time element is of extreme importance in every estimating job. Not only is it applicable to the actual length of time needed to produce the parts. The delivery date must further include the time to receive raw materials and the time to inspect products and do adjustments if they are necessary.

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DIE COST ESTIMATING

The actual span of time before the arrival of parts at the client's door is vital with reference to the time interval promised: if 5 to 6 weeks are estimated for the delivery, which is more valid, 5 weeks or 6? And what does such a number of weeks really mean—is it the time the products leave the gate of the manufacturer, or does it mark the time of their arrival at the client's place?

Is it possible that the receiving party expects their quality control procedures to be included in those 5 to 6 weeks? In such a case the 5 to 6 weeks' interval will mean the time of the physical placement of parts or tooling in service on the client's production line. Such conditions of sale may be very disagreeable if—for example—the client's quality control finds some problems and will demand them repaired prior to the end of the 5 to 6 weeks' period. After all, this may be the time when their brand new mass production was scheduled to begin, and the parts contracted for that better be there.

Even though such delivery arrangements are not common, they may sometimes be demanded, especially where a delivery to the heavily scheduled production line is being made. Estimators and engineers must therefore be aware of all such little ambiguities and possible misunderstanding, which they may not be familiar with but which nevertheless exist. They must carefully guard the wording of the quotation, specifying each term in clear and understandable language. After all, an estimate becomes a binding contract once accepted.

The form of submission of the quotation should be somewhat standardized and well thought over. It may utilize generally known statements, such as:

- COD, cash-on-delivery or collect-on-delivery, means the merchandise is to be deposited with the receiving party only after all costs are settled with either the shipper or the vendor's trucker. Such costs, often payable in cash, will certainly consist of the shipping charges, usually combined with the total cost of the merchandise.
- FOB, or freight-on-board or free-on-board, means that the cost and shipping terms of the estimate are valid up to the point when the merchandise is placed with the shipping forwarder. At that moment, a copy of the bill of lading must be submitted to the buyer, who takes full responsibility for the shipping changes. FOB New York means that the merchandise is brought to the shipyard (or a train station or a trucking terminal) in New York, and all subsequent expenses are the buyer's responsibility.
- FAS, or free-alongside-ship, has a similar meaning to FOB.
- EX, or ex factory, ex warehouse, ex city, or ex origin are additional clarifications of FOB.
- CIF, or cost-insurance-freight. CIF New York means that the merchandise is delivered to the New York port (or railroad station or trucking company) with its passage and insurance fully paid by the seller up to that point. If such merchandise is coming from Africa, the cost of shipping includes the cost of its ocean passage. The buyer must receive from the seller the bill of lading, an invoice, an insurance agreement, and a receipt, confirming the payment of shipping costs. A shipping brokerage firm or a customs broker has to be contracted afterward to handle all other processing procedures involved in a sea trade, overseas, and international shipments.
- C and F, a variation of CIF, meaning cost-and-freight, without insurance.
- ARO—on receipt of an order, or after receipt of an order.
- Bill of lading is an agreement between the seller and the shipper specifying the terms of the shipping contract, while at the same time serving as the receipt for the goods accepted by the shipper. A copy of the bill of lading must be forwarded to the buyer, which indicates ownership. Anyone presenting a bill of lading to the shipper may claim the merchandise.
- Invoice, or pro-forma invoice (needed mainly with international transactions), is a document prepared by the manufacturer of goods, which must list the merchandise shipped, its costs, and place of manufacture. This statement is necessary for the shipping brokerage

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firm or a customs broker, who will handle the procedures necessary for allowing the shipment to enter the country.

- Lead time is the length of the production period. There are various types of lead times. There may be a lead time on design, lead time on the first piece inspection, or lead time on a production run. Each of these time intervals covers a different span of time, specified in detail within the estimate, as shown in Fig. 15-7.
- Terms: Net 30 days. This phrase means that if the seller receives full payment within 30 days after the delivery of goods, the price will be as shown. Any additional time span will accumulate an interest percentage. Sometimes the amount of such a percentage may be specified alongside, for example, Net 30 days 1½ percent. This means that every additional month or fraction of it that the payment is overdue will cause the original amount to increase 1½ percent.

An offer shown in Fig. 15-7, when translated into everyday language, means that we are willing to design a die, to produce part no. AK-386-C Revision C, for the amount of US$3,500 and subsequently build such a tool for an additional US$40,000. We will start working on the design only when we receive a written and signed order (ARO), accompanied by a check for the first third of the total sum, or $14,500. The design stage will be completed in 4 weeks from the day the order and the check arrive.

(Today's date)

1. Die design, per Dwg. No. AK-386-C, Rev. C — $3,500.00
   Lead time: 4 weeks ARO
2. Die manufacture, per design shown above — $40,000.00
3. Twelve (12) preproduction samples submitted for inspection
   Lead time: 6 weeks after design approval
4. Production run:
   1,000 Pcs. $3.95 Ea.
   5,000 Pcs. $3.50 Ea.
   10,000 Pcs. $3.15 Ea.
   50,000 Pcs. $3.10 Ea.
   100,000 Pcs. $3.05 Ea.

Delivery schedule:

First 1,000 Pcs. — 1 week after approval of preproduction of samples
Each 10,000 Pcs. — 2–4 weeks production lead time

Method of payment:

One-third (⅓) of the total amount (or $14,500.00) to accompany the order
One-third (⅓) of the total amount (or $14,500.00) payable on receipt of preproduction samples
One-third (⅓) of the total amount (or $14,500.00) payable on the approval of preproduction samples

Terms:

Net 30 days.
All prices are quoted in US dollars
Delivery terms: FOB origin
Expiration of the quote: 2 months from the date shown above

FIGURE 15-7 Cost estimating format—lead time, delivery, and payment scheduling.

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After such a span of time we must submit the finished design for approval. The client may express approval at leisure, but only after we receive written consent with the submitted design shall we proceed with actual manufacture of the die. It is of no consequence how long it will take us to build the die, but we must submit the first 12 pieces of parts produced by that tooling within 6 weeks from the time the client approved the design.

On submission of preproduction samples, another check must be sent to us, or another bank transfer of funds for an additional $14,500 must take place, regardless of whether the samples are approved by the client or not.

Within a week of approval of preproduction samples, accompanied by a check for the last portion of total cost, 1000 production pieces must be sent to the client. Naturally, these production pieces will be charged separately, at $3.95 each, depending on the total number ordered.

Should preproduction samples not be approved, it will be our duty to alter the die in accordance with the client's demands. However, the claim will be valid only if the die would not perform in accordance with drawing number AK-386-C Revision C. If the request for alteration demands the die to produce parts per the next Rev. D or any other previous or subsequent revision, the client must pay for such changes separately.

The lead time on the first 1000 pieces is shortened on purpose. At the time the die is built and tested, the very first pieces must be submitted for inspection within our own plant. On the basis of the quality control outcome we actually already know whether the die performs properly or not. While running the 12 preproduction samples for the client, it usually pays to include the first 1000 or so, to eliminate the extra setup required otherwise.

The clause "All prices are quoted in U.S. dollars" is important when sending or receiving a quote from a foreign country. Most of us assume the dollar as a currency term to be an American unit only, but this is wrong. There are Canadian dollars, Hong Kong dollars, Singapore dollars, New Zealand and Australian dollars, East Caribbean dollars, Slovenian tollar, Liberian dollars, Solomon Island dollars, and who knows what additional dollars financiers may come up with. The main problem with these variations of currency is that each has a different value and is affected by that currency fluctuation. It is therefore best to specify the amount to be paid in U.S. funds.

Overseas manufacturers do not like this trend at all, because if their currency changes value in comparison with the U.S. dollar, they may actually suffer a loss on the business deal. Evaluation of this problem and its solution exceeds the scope of a die design handbook, and it will not be discussed further. It may suffice to suggest that there are several strategies to hedge against a probable or anticipated loss due to international currency exchange rate fluctuations, like, stop transactions, currency options, forward contracts, currency futures, and so on. There is, naturally, a cost involved in adopting these hedging tools.

Naturally, when estimating the delivery of parts, the component that takes the longest time to obtain is used as a guideline. Anyway, what good it will be to promise delivery of 1000 compression springs within 2 weeks if it takes 4 weeks to get the raw material and we have none in stock?

15-5-2 Packaging and Shipping

Products may be perfect when produced, but if the packaging was not designed properly, they may become damaged by the time they get to the client. We all know that we should not package a set of engraved crystal wire glasses in a paper box. But few can imagine what happens to sheet-metal parts that are thrown haphazardly into a container and sent out by "Your-Good-Neighbor" forwarder.

When a multitude of relatively cheap parts are packaged, the cost of organizing them in layers, placing protective sheets or barriers in between, and placing each package, not

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heavier than 25 lb, in a wooden crate, sealed for shipping would be outrageously high in comparison with the cost of parts. Therefore, sheet-metal parts are usually sent out in barrels or in other types of containers that are often returned to the supplier.

How many pieces may be placed in a single container without damaging the bottom layers? This assessment is usually based on the approximate weight the contents of the container will exert on its bottom. Therefore, the height of the container, as well as the method of stacking containers on the truck, is crucial.

Except for flat round shapes, sheet-metal parts tend to get scratched when packaged in drums. Sometimes they must be separated in layers with protective barriers in between. The packaging containers may also need to be smaller. But all these alterations are very costly, and if that is not included in the original estimate, guess who will foot the bill?

For obvious reasons, it is preferable to specify the problem of packaging right at the beginning, write the terms into the estimate or contract, and include the cost of any extras. A client who demands that each layer of flat, 1-in.^{2} parts of 0.062-in. thickness be separated by a neoprene sheeting should have it—but at a price.

When shipping overseas, the rules are somewhat different, and appropriate packaging is much more costly and demanding. Restrictions are placed on what must be written on the shipping container and how. Relative heights of various lettering are important, and the (last) country of origin must be specified according to the customs-issued rules and regulations. Often, a double packaging is used, the first being the original container and the second a shipping crate.

Additional problems may arise when selecting an appropriate shipper, in the absence of in-house trucking. Naturally, the cost of shipping is of essence here, but that's only a small portion of the problem. Loading and unloading methods may be detrimental to the whole order. Shaking of the truck on the road may force parts to vibrate and scratch their surfaces. When accidentally dropped, damage-prone items will certainly become damaged. And what if the package is loaded wrong side up? Yes, we know that the safety of the merchandise's passage is often the shipper's responsibility. But will buyers continue to order from us if the parts always arrive damaged?

A standard drop test for shipping purposes, used by major shipping contractors, is conducted from the height of 3 feet, and tested parts, in their original packaging, should land on at least three sides, two edges and one corner. This sentence should tell us all about the dangers of shipping. Of another concern is the fact that shipping rates vary with respect to the category the goods may be considered belonging to. Basic, unpainted products will be delivered for less than painted parts, with painted assemblies being still higher. Be wary of the shipping classes before uploading your merchandise on the truck bed. If the shipper decides your merchandise belongs to a different class than that which was quoted, the shipping cost will go up.

15-5-3 Extra Costs and Regulations

Extra costs may be incurred everywhere if something is omitted or forgotten. Shipping companies charge a fee for storage if the merchandise is not picked up or cannot be delivered on time. A vendor charges a fee if the approval of samples is not on time and the setup machine has to stand by, waiting. There will be a fee for changing money from one currency to another, a charge for a payment by a letter of credit, a charge for late-received payment, and so on. Shipping brokers charge a fee (usually a flat fee, for example, $200 per shipment of any size) to issue the accompanying papers. There may be fees for loading and unloading of the merchandise when sending it out or receiving it. There are fees and payments and payments and fees. They must all be added up somewhere, and it better be within the cost estimate.

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Customs fees are of additional concern to those who may think of importing or exporting. Customs fees may run from zero percent of the merchandise's value up to 50 percent. Perhaps some items may run still higher, who knows; these tariffs tend to change quickly and without any warning.

The range of these fees is so wide and so diverse that it really pays to get in touch with the Bureau of Customs and ask specifically about each exported or imported item, specifying its function and usage, because even the product's usage, the advancement of assembly, the finalization of finishing, and other pertinent details matter when it comes to customs fees.

However, sometimes these fees can be altered in our favor, and it is perfectly legal. For example, let us say the tariff for cultured pearls is 2.5 percent and that for cut, nonset stones starts at zero, up to 5 percent. Now, if we import these two types of merchandise and manufacture gilded sheet-metal back scratchers, set with real pearls and precious stones, we will be getting quite a deal on such a business proposal, especially when considering that duties on completed jewelry items run between 12 and 27.5 percent.

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